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SUPREM II -- A PROGRAM FOR IC PROCESS MODELING AND SIMULATION.(U)

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SUPREM II -- A PROGRAM FOR IC PROCESS MODELING AND SIMULATION

by

Dimitri A. Antoniadis, Stephen E. Hansen, and
Robert W. Dutton

June 1978

Technical Report No. 5019-2

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PREFACE

SUPREM II is the second version of the Stanford University IC process simulation program, SUPREM. Several modifications and refinements relative to SUPREM I [1] have been implemented but the basic program architecture and I/O philosophy has not been altered. The input language syntax remains the same, but various semantic changes have been made mainly to accommodate the new or improved physical models used in SUPREM II. Also, CPU time saving features have been included, the most important one being the introduction of latent regions in the simulated space where the impurity distributions are not processed until they exceed a physically significant level of concentration. In this new version of the program the probability of numerical instability such as the occurrence of negative impurity concentrations, has been greatly reduced by the implementation of a new segregation model. Among new physical processes that are now simulated by SUPREM II are, phosphorus diffusion under high concentration and the associated base push, arsenic clustering which affects both arsenic migration and final electrical activity, and enhanced oxidation rates due to high surface concentration of n- and p-type impurities.

This report consists of three parts. In the main part the physical process models and their numerical implementation in SUPREM II are described. Also, some details of the program and data structure are discussed. The second part (Appendix 1) contains the SUPREM II operating manual valid at the time of the program release. The last part of the report (Appendix 2) consists of a set of examples of program usage in multi-step process simulation together with some of the resulting outputs.

1. INTRODUCTION

The Stanford University Process Engineering Models (SUPREM) program is a computer simulator capable of simulating most typical IC fabrication steps. The program is designed so that these steps can be simulated either individually or sequentially, just as they would occur during the actual fabrication process. The output of the program, available at the end of each step, consists of the one-dimensional profiles of all the dopants present in the silicon and silicon-dioxide materials. These profiles may be displayed in various formats including line-printer output, line-printer plots, and high-resolution (Calcomp type) plot. It is understood that, in sequential step simulation, the output of a processing step constitutes the initial conditions for the subsequent step. The junction depths and sheet resistances of all n or p layers formed during the process are also calculated.

The fabrication step simulation is based on several process models. The models implemented in SUPREM are the following:

- (a) ion implantation
- (b) chemical predeposition through the surface (gaseous or solid)
- (c) oxidation/drive-in
- (d) epitaxial growth
- (e) etching
- (f) oxide deposition

Migration of impurities is fully accounted for in any of the above models involving high temperature.

Communication between the user and SUPREM II has been kept as simple as possible. The input file consists of free format statements involving key words and numbers. Typically, a single processing step can be simulated with an input specification involving less than 60 alphanumeric characters. The details of input specification are given in the SUPREM II user manual (Appendix 1).

Several physical parameters have been stored in the program and constitute the default values used by the models. These values are given in Appendix 1 with the appropriate references. They may be overridden by user-specified parameters.

The various process models have been implemented in SUPREM as subprograms, each consisting of a number of subroutines and special functions. Figure 1 is a schematic of this arrangement. Input parameter specifications have been designed to resemble actual process runsheet data and documentation. A run may consist of a series of process steps. A typical input file is listed in Appendix 2. The sequence of steps and the specification of the correct model parameters are controlled by a supervisor program that evokes the appropriate step subprogram. All communication between the various subprograms is directed through the common variable area of the computer memory.

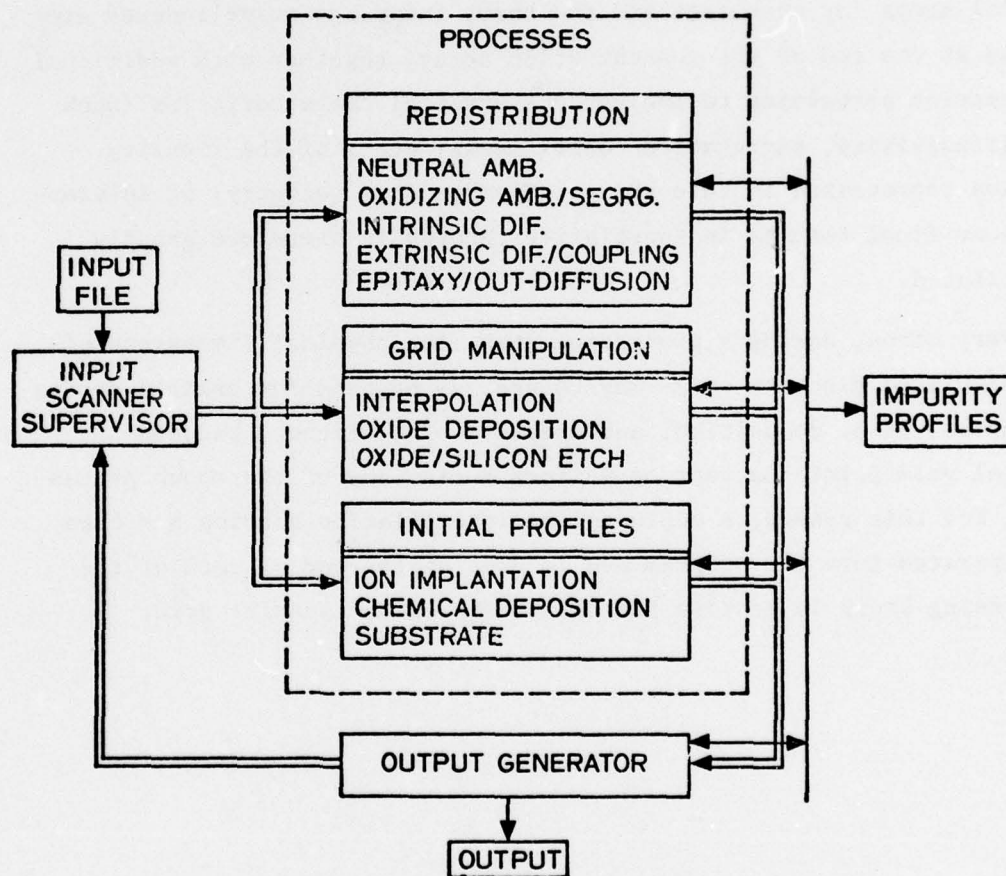


Figure 1 General block diagram of the SUPREM process simulator.

One essential part of the common area contains the impurity concentration arrays. In the present version of SUPREM, there is a capability for handling up to three different impurity species. The impurity concentration is stored in terms of a discrete profile with a maximum number of 400 points. Each concentration value corresponds to a point in the discrete space (spatial grid) defined along a vertical axis, with its origin at the surface of the material -- silicon (Si) or silicon dioxide (SiO_2). Typically, the spatial grid is divided into the SiO_2 grid points, high-resolution-depth grid points, and low-resolution grid points, as illustrated in Appendix 1. Within each of the above three areas, the grid-point separation is uniform. The spatial steps for each area and the three interface point indexes are stored at the end of the concentration array, together with additional information pertaining to the various physical characteristics (such as diffusivities, segregation coefficients, etc.) of the impurity species represented in this array. Storage (and recovery) of intermediate or final results in nonvolatile records is therefore greatly facilitated.

Very often, during a processing step, the physical dimensions of the simulated discrete space may change, as happens for example during oxidation, etch, deposition, and epitaxy. The distance between spatial grid points may not be uniform during any of the above processes. For this reason, a cubic spline interpolation routine has been incorporated into the program and is used at the end of each of the processing steps to restore the uniformity of the spatial grid.

2. PROCESS MODELS

2.1 Ion Implantation Model

The simplest description of an implanted impurity profile in silicon or silicon dioxide is a symmetrical gaussian curve with first two moments the projected range, R_p , and the standard deviation, σ_p , calculated from the LSS theory [2]. However, experimental distributions of many ions, such as boron or arsenic are found to be assymetrical. The simple gaussian approximation of those implanted profiles is often inadequate so that higher-order moments must be used to construct range distributions. Gibbons and Mylroie [3] have shown that the third central moment is enough to provide sufficient information to construct accurate distributions when the asymmetry is not excessive (less than the standard deviation). In these cases, the distribution can be represented by two half-gaussian profiles, each with a different standard deviation, σ_1 and σ_2 , joined together at a modal range R_m as shown in Figure 2. This method is used to specify the implanted profile of all impurities in SUPREM II, with the exception of boron where a modified Pearson IV distribution is used as described later.

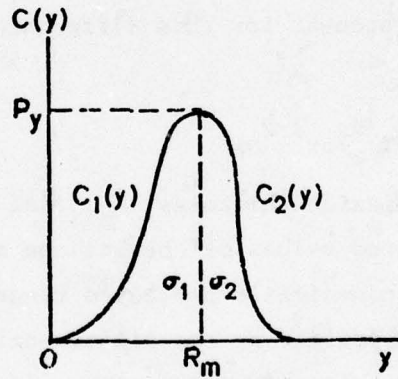


Figure 2 The joint half gaussian representation of as-implanted impurity profiles

For the joint half-gaussian distribution, the two sides are given by

$$C_1(y) = P_x \exp \left[- (y - R_m)^2 / 2\sigma_1^2 \right] \quad 0 \leq y \leq R_m$$

$$C_2(y) = P_x \exp \left[- (y - R_m)^2 / 2\sigma_2^2 \right] \quad R_m < y \leq \infty$$

In SUPREM II, the values for R_m , σ_1 and σ_2 are obtained from the Gibbons-Mylroie algorithm which makes use of R_p , σ_p , and of the third moment ratio, γ_1 . These last three quantities are obtained by interpolation from look-up tables for each element in silicon or silicon dioxide as a function of implant energy [4]. In addition to the acceleration energy, the normal way of specifying an implant is by selecting the ion dose. As a result, a relationship between the dose and peak concentration must be used. Defining the normalized ion dose by

$$Q(\sigma, R, a, b) = \int_a^b \exp [-(y-R)^2/2\sigma^2] dy$$

The peak concentration, P_y , and the total dose, Q , are related by

$$P_y = Q/[Q(\sigma_1, R_m, 0, R_m) + Q(\sigma_2, R_m, R_m, \infty)]$$

In implantation through silicon dioxide, two sets of σ_1 , σ_2 , and R_m must be used in the two regions. Because the stopping power of silicon dioxide is somewhat different from that of silicon, the modal range in silicon is modified to account for this difference in the following approximate way,

$$R'_{mSi} = R_{mSi} + (1 - R_{PSi}/R_{Pox}) Z_{ox}$$

where Z_{ox} is the silicon dioxide thickness, R'_{mSi} and R_{mSi} are the corrected and the uncorrected values of the silicon modal range, and R_{PSi} and R_{Pox} are the silicon-dioxide projected ranges. A possible small discontinuity of the profile at the silicon-oxide interface is an artifact produced by this approximation.

Boron implanted profiles: Hofker et al [5] have shown that the implanted boron profiles, before annealing, may be described by a Pearson type IV distribution. They have experimentally determined the fourth moment ratio, β_2 . Although this distribution describes well the profile of boron from the surface to a distance somewhat beyond the peak of distribution, Figure 3 shows that the approximation fails to model the

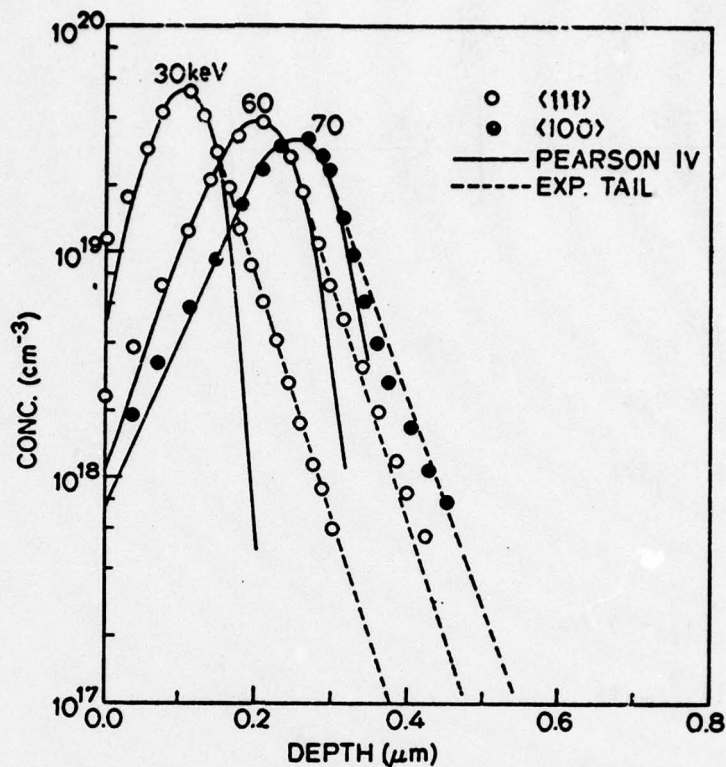


Figure 3 Boron as-implanted profiles in $\langle 111 \rangle$ and $\langle 100 \rangle$ silicon in a random direction. Pearson IV and modified Pearson IV distributions for representation of these profiles.

observed exponential tail that is due to random scattering of boron ions along channeling directions. Based on experimental results [6,7,8] we have empirically modified the Pearson IV distribution by adding an exponential tail with a fixed characteristic length ($0.045 \mu\text{m}$), independent of dose energy and crystalline surface orientation. The tail is attached to the shoulder of the standard Pearson IV distribution where the concentration drops to 50% of the peak value. Of course after the addition of the tail, renormalization of the distribution to the implanted ion dose is carried out. Typical resulting profiles from this modification are shown in Figure 3.

The standard Pearson IV distribution is calculated as follows:

$$C(y) = C_0 e^{f(y)}$$

where

$$f(y) = \frac{1}{2b_2} \ln |b_0 + b_1 x_n + b_2 x_n^2| - \frac{(b_1/b_2 + 2a)}{(4b_2b_0 - b_1^2)^{1/2}} \tan^{-1} \left[\frac{2b_2 x_n + b_1}{(4b_2b_0 - b_1^2)^{1/2}} \right]$$

and

$$x_n = (y - R_p) / \sigma_p$$

$$a = -\gamma_1(\beta_2 + 3)/A$$

$$b_0 = -(4\beta_2 - 3\gamma_1^2)/A$$

$$b_1 = a$$

$$b_2 = -(2\beta_2 - 3\gamma_1^2 - 6)/A$$

$$\text{and } A = 10\beta_2 - 12\gamma_1^2 - 18$$

The constant C_0 is found from a normalization to the implanted dose:

$$A = Q / \int e^{f(y)} dy$$

2.2 Impurity migration during thermal processing

2.2.1 Introduction. The redistribution of impurities in the space of the silicon-silicon dioxide system, during thermal processing, is governed by the general continuity equation which can be written as

$$\frac{d}{dt} \int_{V(t)} C dV = \int_{V(t)} (g - \ell) dV - \oint_{S(t)} \vec{F} \cdot \vec{n} dS \quad (1)$$

where

C = impurity concentration

$S(t)$ = closed surface (function of time, t)

$V(t)$ = volume enclosed by $S(t)$

\vec{F} = impurity flux vector

\vec{n} = outward unit normal to $S(t)$

g = impurity generation rate per unit volume

ℓ = impurity loss rate per unit volume

The left hand side of equation (1) represents the time rate of change of the impurity content in any volume, $V(t)$, and it is equated to the net impurity generation rate in the same volume minus the net impurity outflow through the surface $S(t)$ enclosing $V(t)$. The reason for using the continuity equation in integral form is that it simplifies treatment of volume changes which occur during silicon oxidation and epitaxy processes. The generation and loss mechanisms have been included to account for the exchange of impurity atoms between different states in the silicon lattice as in the case of arsenic where atoms may coexist in substitutional and clustered states.

For one dimensional flow, equation (1) can be written

$$\frac{d}{dt} Q(y_1, y_2) = U(y_1, y_2) - [F(y_2) - F(y_1)] \quad (2)$$

where

$$Q(y_1, y_2) = \int_{y_1}^{y_2} C(y) dy \quad (3)$$

$$U(y_1, y_2) = \int_{y_1}^{y_2} (g - \ell) dy \quad (4)$$

where y is the direction perpendicular to the silicon surface and is positive inwards, and the flux $F(y)$ is positive in the y direction. Physically, the impurity flux may arise from thermal diffusion, from interface phenomena such as evaporation or segregation and from the motion of interfaces as in the case of silicon oxidation and epitaxy.

In the sections that follow we discuss the models used to describe each of the physical processes present in equation (2) as well as their numerical implementation in the context of SUPREM II.

2.2.2 Diffusive flux. Solid state diffusion is the physical mechanism responsible for impurity migration within the silicon body during high-temperature processing steps. At any point, y , the diffusive flux, $F_D(y)$, of impurities is related to their concentration and diffusivity gradient by the modified Fick's first law [9]. For one-dimensional flow the relation is

$$F_D(y) = - \frac{d}{dy} (D(y) \cdot C(y)) \quad (5)$$

where $D(y)$ is the diffusion coefficient of the impurity. Under the assumption of single-state migration there is no generation or loss within the material. The conservation equation, therefore, becomes

$$\frac{dQ(y_1, y_2)}{dt} = - (F_D(y_2) - F_D(y_1)) \quad (6)$$

Under the further assumption of uniform diffusivity, the well-known Fick's second law is derived by using equations (3) and (5) in (6) and differentiating with respect to y . The equation becomes

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial y^2} \quad (7)$$

Fick's second law is generally adequate for the calculation of impurity migration under low impurity concentration conditions. However, this approximation fails as the impurity concentration increases to or above the intrinsic carrier concentration, $n_i(T)$, in the semiconductor at the process temperature. Figure 4 is a plot of n_i vs temperature as defaulted in SUPREM II [10]. In addition, equation (7) may fail even at low concentration conditions if another impurity species is present in the silicon at high concentration. We refer to silicon in which any impurities exist at concentrations lower than $n_i(T)$ at the process temperature, as intrinsic silicon. If the opposite is true then we refer to it as extrinsic.

One of the first attempts to explain diffusive flux under extrinsic conditions was to include the "electric field effect" of the introduced free carriers on the impurity ion migration [11], in a way similar to ambipolar diffusion in plasmas. The effective diffusion coefficient

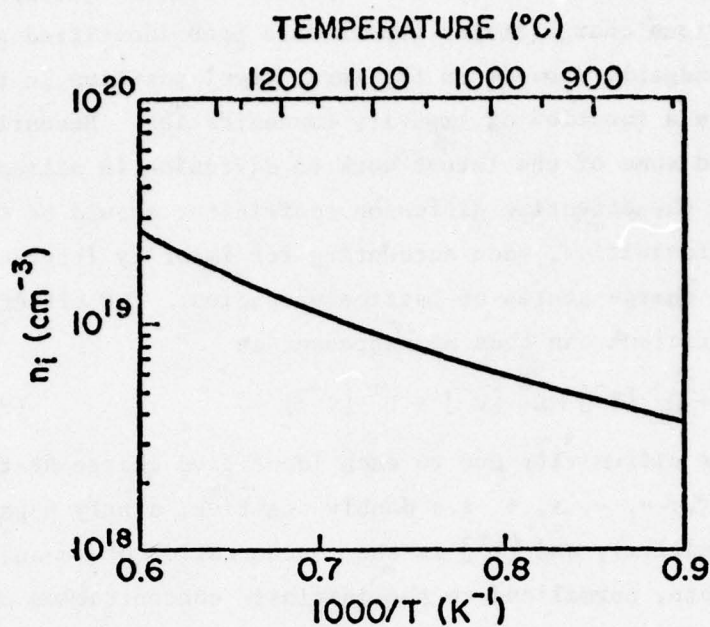


Figure 4 Intrinsic carrier concentration in silicon vs temperature.

thus becomes a function of impurity concentration given by

$$D = D_i f_e = D_i \left\{ 1 + \left[1 + 4 \left(\frac{n_i}{C} \right)^2 \right]^{-\frac{1}{2}} \right\} \quad (8)$$

where D_i is the intrinsic diffusion coefficient. As can be seen, the maximum value of f_e is 2, for $C \gg n_i$ and this is clearly inadequate to explain diffusivity enhancements of the order of 10 to 20 often observed with most of the common impurities.

At present, it is generally accepted that extrinsic diffusion phenomena are the result of impurity migration by interaction with charged point defects in silicon [12]. All common impurities diffuse in silicon by means of interaction with lattice point defects such as silicon atom vacancies and possibly interstitials. Thus, the diffusion coefficient is proportional to the concentration of such point defects. Although the concentration of neutral defects at any given

temperature is dependent on the impurity concentration (so long as it does not approach that of silicon atoms), the concentration of defects at various charge states (which have been identified within the silicon bandgap), depends on the Fermi level position in the band-gap and thus is a function of impurity concentration. Recently Fair [13] summarized some of the latest work on diffusion in silicon and suggested that the effective diffusion coefficient should be the sum of several diffusivities, each accounting for impurity interactions with different charge states of lattice vacancies. The effective diffusion coefficient can thus be expressed as

$$D = f_e \{D^x + D^- [V^-] + D^= [V^=] + D^+ [V^+]\} \quad (9)$$

where D^v is the diffusivity due to each identified charge state, v , of vacancies, (v : =, -, x, + i.e doubly negative, singly negative, neutral and positive), and $[V^v]$ is the concentration of vacancies in each charge state, normalized to the intrinsic concentration of that state. Using Boltzmann approximation it can be easily shown that these normalized concentrations may be given by

$$[V^-] = \frac{n}{n_i}, [V^=] = \left(\frac{n}{n_i}\right)^2 \text{ and } [V^+] = \frac{n_i}{n} \quad (10)$$

where n is the free electron concentration. Thus, under intrinsic conditions ($n=n_i$), equation (9) becomes

$$D_i = D^v + D^- + D^= + D^+ \quad (11)$$

i.e the intrinsic diffusivity is the sum of the diffusivities resulting from the various vacancy charge states.

The above model is the basis of what has been implemented in SUPREM II. However, with the exception of phosphorus, it has been assumed that only the neutral and one charged defect state is responsible for the diffusivity of impurity atoms. The specific form now used in the program is

$$D = D_i (1 + \beta f_v) / (1 + \beta) \quad (12)$$

where D_i is the measured intrinsic diffusivity and $f_v = n/n_i$ for donors and n_i/n for acceptors. Thus, under intrinsic conditions $f_v = 1$ and

$D = D_i$. On the other hand for extrinsic conditions the physical meaning of the parameter β can be derived by combining equations (9), (10) and (12), to get

$$D^X = D_i \frac{1}{1 + \beta} \quad \text{and} \quad D^V = D_i \frac{\beta}{1 + \beta}$$

Thus, $\beta = D^V/D^X$, is an index of the effectiveness of charged vacancies relative to neutral ones in impurity diffusion. Figure 5 is a plot of normalized diffusivity vs. f_v . Although it might be expected that β for any impurity element is a function of temperature, no definite characterizations exist at present. Recommended values (also included in the program as defaults) are $\beta = 3$ for boron and $\beta = 100$ for arsenic while for phosphorus a completely different model is used as described later. β is not known for other impurities and therefore is defaulted to 1.

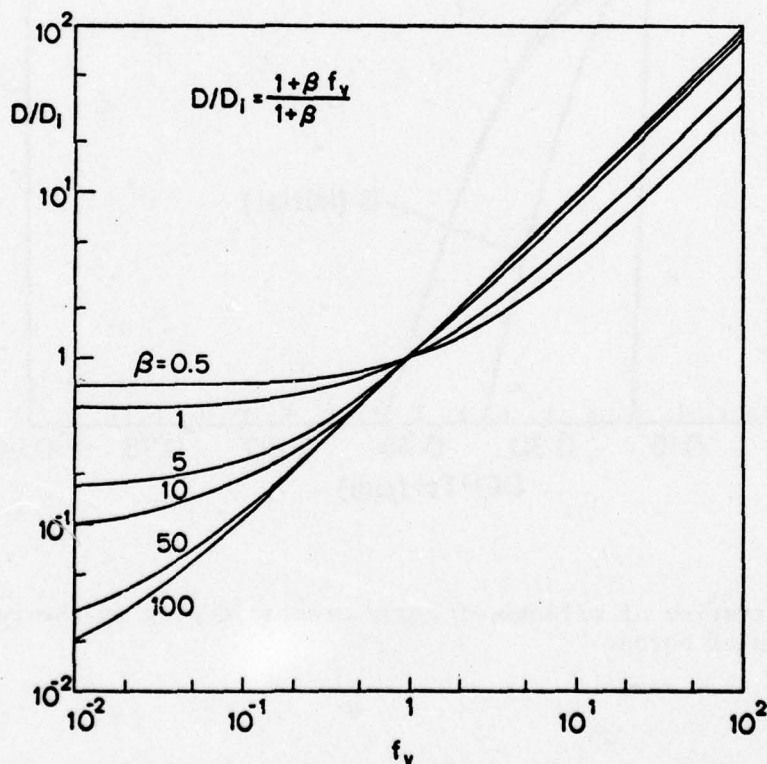


Figure 5 Normalized diffusivity vs normalized carrier concentration for different values of β .

It is well known that when different impurity atoms are present in silicon there is direct interaction among them [14]. Fig. 6 illustrates one such (simulated) case where high concentration arsenic effects the distribution of boron*. In SUPREM II this interaction is directly

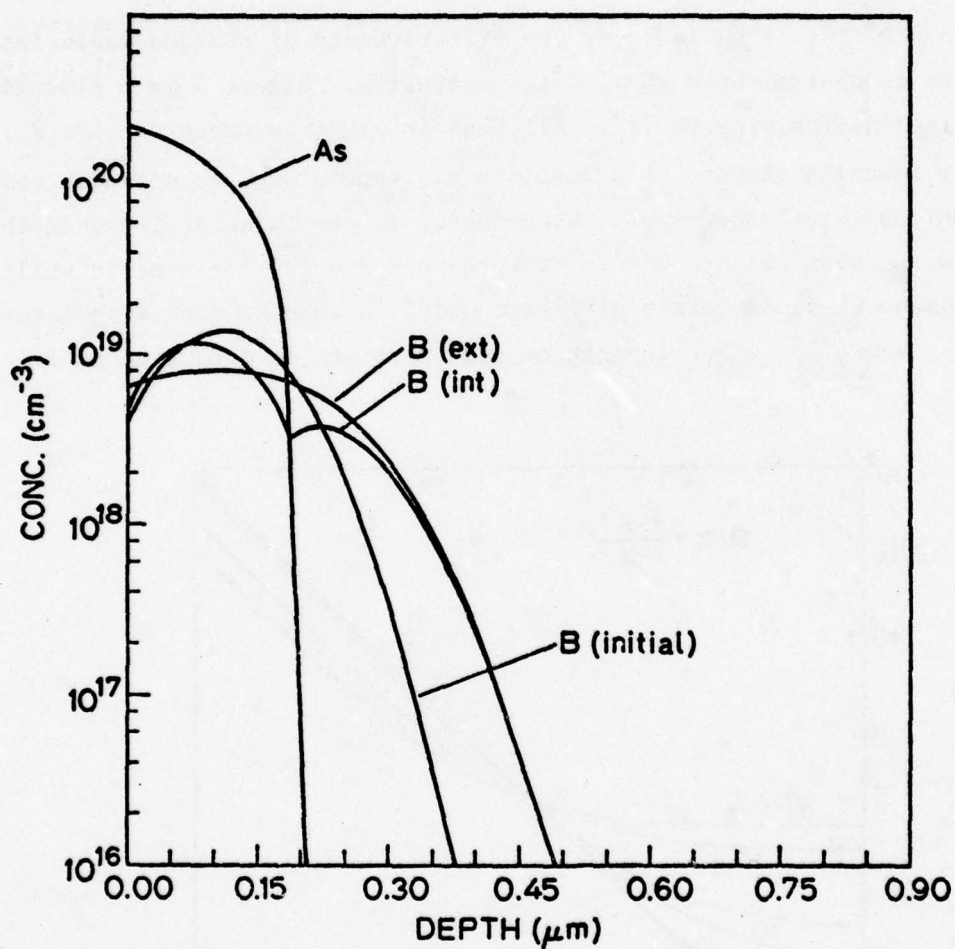


Figure 6 Illustration of effects of heavy arsenic doping on the redistribution of boron.

*The case of phosphorus is quite different. As explained later, phosphorus at high surface concentration indirectly affects the diffusivity of other impurities by increasing the concentration of point defects in silicon.

modeled through the use of equation (5) for the calculation of impurity flux. For the example shown in Figure 6 the diffusive flux of boron in the region which is heavily n-doped is reduced because $f_v(\text{boron}) = n_i/n \rightarrow 0$, while at the edge of the arsenic profile the dip is produced by the rapid spacial change of f_v and thus of diffusivity for boron.

Phosphorus: The model implemented in SUPREM for the diffusive migration of phosphorus has been presented by Fairand Tsai [15]. The model predicts with reasonable accuracy the phosphorus kink formation as well as the base push effect, commonly observed during heavy emitter diffusions in bipolar technology. According to this model the physical explanation of these "anomalous" effects lies in the enhancement of vacancy concentration in the silicon caused by the dissociation of the phosphorus-doubly ionized vacancy pairs that flow from the surface into the silicon bulk. A typical high concentration phosphorus profile is composed of three regions as shown schematically in Figure 7a.

- (a) The surface region in which phosphorus diffusion is assumed to take place by interaction with neutral and with doubly charged vacancies forming P^+V^- pairs. In this region the diffusivity is given by

$$D = f_e \left(D^x + D \left(\frac{n}{n_i} \right)^2 \right)$$

where n , the free electron concentration is calculated from the total phosphorus concentration using equation (48). Thus in this region the diffusivity is monotonically decreasing, as shown in Figure 7a. The end of the surface region is assumed to lie at the point where the Fermi level drops below .11 eV from the conduction band which is identified as the state level for doubly ionized vacancies. This occurs at a characteristic electron concentration, n_e , given by

$$n_e(T) = 4.65 \times 10^{21} \exp \left(- \frac{0.39 \text{ eV}}{kT} \right)$$

- (b) The tail region where the diffusivity is enhanced relative to the intrinsic value due to supersaturation of the silicon lattice by vacancies resulting from the P^+V^- dissociation.

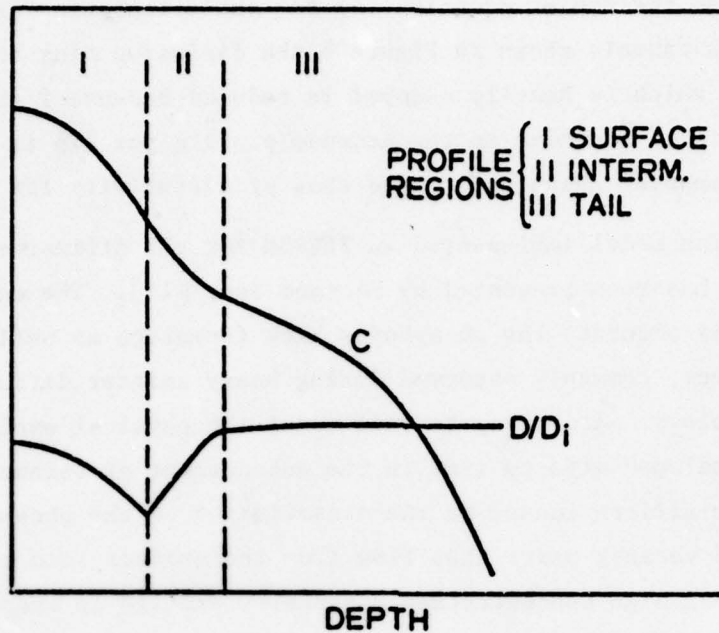


Figure 7a A typical phosphorus doping profile with a demarcation of the three regions considered by the Fair and Tsai model. Also shown is the local diffusivity profile derived by the model.

In this region the diffusivity is given by

$$D_{TAIL} = f_e \left\{ D^x + D^- \frac{n_s^3}{n_e^2 n_i} \left[1 + \exp \left(\frac{0.3 \text{ eV}}{kT} \right) \right] \right\} \quad (13)$$

where n_s is the surface electron concentration. This equation should only be considered as an empirical fit to observations. As can be seen the tail diffusivity depends very strongly on n_s and thus the surface concentration of phosphorus. Since the model predicts that there exists a vacancy defect supersaturation in the bulk, a point that has been recently verified by Matsumoto et al [16], any other impurity elements present in the silicon lattice beneath a region of heavy phosphorus surface concentration should also experience a diffusivity enhancement approximately equal to that of phosphorus. Thus, in SUPREM II

an enhancement factor, f_{enh} , given by

$$f_{\text{enh}} = \frac{D_{\text{TAIL}}}{f_e D^x}$$

is calculated and multiplies the intrinsic diffusivity, D^x , of any other impurity in the presence of phosphorus. This treatment permits the modeling of the base push effect, but also predicts an enhancement of diffusivity of other elements such as arsenic or antimony that may constitute the buried collector in bipolar processes. This latter effect is proposed by the present authors, and has yet to be experimentally confirmed.

The beginning of the tail region is determined as follows: It has been observed by means of Boltzmann-Matano analysis of phosphorus profiles under heavy doping conditions [15,17] that there exists an intermediate region between the surface and the tail, where the diffusivity increases in proportion to $\left(\frac{n_i}{n}\right)^2$. This empirical observation is used in SUPREM II to determine the beginning of the tail region. Namely, the diffusivity calculated at the end of the surface region, i.e. at the point where $n = n_e$, is multiplied by $\left(\frac{n_i}{n}\right)^2$, as the depth from the surface increases, until the point where the value D_{TAIL} is reached. At that point the tail region is assumed to begin.

It can be easily seen from equation (13) that the model just described predicts that the diffusivity of phosphorus, at least in the tail region, should increase monotonically with increasing surface concentration. It is however well known that as the surface concentration increases above about $3-4 \times 10^{20} \text{ cm}^{-3}$ the tail diffusivity decreases. This effect may be attributed (Fair [18]), to silicon bandgap narrowing due to the stress induced on the lattice by the high phosphorus concentration. In SUPREM II this stress effect is modeled by increasing the intrinsic carrier concentration, n_i , according to the formula

$$n_i = n_i \text{ (unstressed) } \exp \left(- \frac{\Delta E_g}{kT} \right)$$

where ΔE_g is the stress-induced bandgap narrowing given by the equation [18]

$$\Delta E_g = - 1.5 \times 10^{22} \left(C_{TS} - 3 \times 10^{20} \text{ cm}^{-3} \right) \text{ eV}$$

where C_{TS} is the total surface concentration of phosphorus. Of course, at the same time n_e must also be increased by the same amount. The importance of including the stress effect is illustrated by Figure 7b where the calculated diffused phosphorus profiles with and without ΔE_g are compared with experimental data.

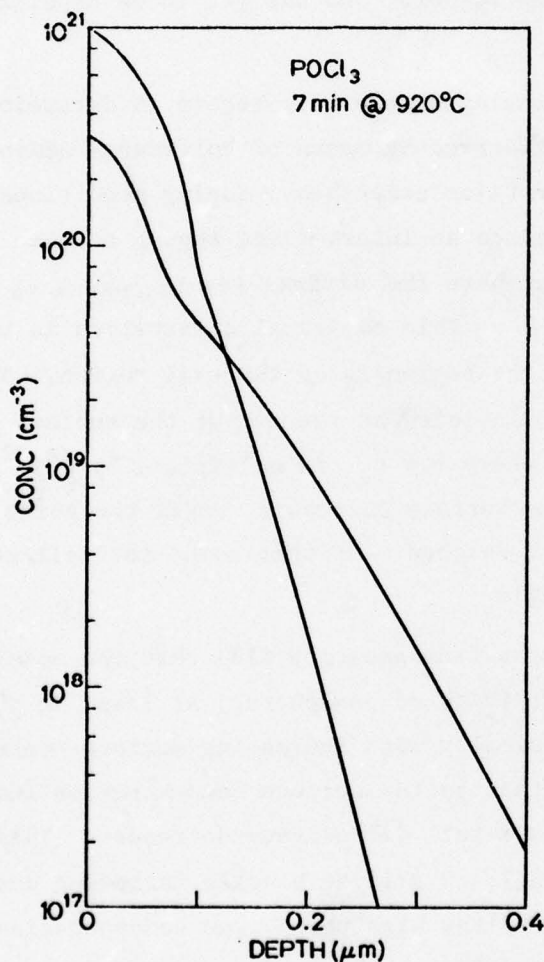


Figure 7b Calculated phosphorus profiles for two different surface concentrations. Slower diffusion of the higher surface concentration profile is due to the silicon stress model.

One additional stress effect also included in SUPREM II affects the diffusivity of ion implanted phosphorus profiles. In this case it is observed that the diffusivity is further decreased under high dose conditions, probably due to permanent lattice disorder [18] produced by the implantation process. Thus, in the case of ion implanted phosphorus an additional bandgap narrowing is calculated from the equation [18]

$$\Delta E_g = - 2.3 \times 10^{-6} (Q_p)^{.25} \text{ eV}$$

where Q_p is the phosphorus atom dose.

2.2.3 Diffusion under non-equilibrium conditions - Oxidation Enhanced Diffusion. It has been observed by several authors [e.g. 19, 20] that the diffusivity of boron and phosphorus is enhanced when the silicon surface is oxidized. This phenomenon of oxidation enhanced diffusion (OED) is generally attributed to enhancement of silicon point defects due to the oxidation. Perhaps the most plausible model has been proposed by Hu [21] and subsequently quantified by Antoniadis et al [20]. This model relates OED with oxidation stacking fault (OSF) growth, by invoking a dual diffusion mechanism for impurities in silicon whereby both vacancy and interstitial defects are responsible for diffusion, and postulating an enhancement, due to oxidation, of the silicon self interstitials. Thus, according to the model, during oxidation the interstitialcy component of impurity diffusivity is enhanced leading to OED while increased interstitial precipitation leads to OSF. At present the relationship between oxidation rate and OED is not known with certainty. Thus, for boron in SUPREM II temperature dependent but time independent OED is assumed for an ambient causing silicon oxidation. For phosphorus a fixed enhancement of a factor 1.8 is assumed for dry O_2 and 3.3 for wet O_2 [18].

2.2.4 Interfacial fluxes. An interface is the surface that separates two different homogeneous regions such as the silicon bulk and the silicon dioxide or the gas ambient. During thermal processing there exists at least one such interface that plays important role in the redistribution of dopant impurities. This may be a bare silicon surface

in an inert ambient where evaporation of impurities is taking place, or the same surface in a dopant atom rich ambient where dopant incorporation takes place or perhaps the silicon-silicon dioxide interface where dopant atom exchange between the two materials is taking place.

Although the actual details of the chemistry taking place at such interfaces may not be known, generally the dopant atom flux across interfaces may be phenomenologically described by means of a first order kinetic model as

$$F_s = h(C_1 - C_2/m_{eq,1-2}) \quad (14)$$

where F_s is the dopant flux defined positive from region 1 to 2, C_1 is the dopant concentration of the interface in region 1 and C_2 the same in region 2. Figure 8 illustrates the setup in the case of a SiO_2/Si interface. $m_{eq,1-2}$ is the equilibrium segregation coefficient for the specific impurity species in the system of regions 1-2 and is defined as

$$m_{eq,1-2} = \frac{C_2}{C_1} \quad (15)$$

Finally, h which has units of velocity, is the surface mass-transfer coefficient.

In SUPREM II, equation (14), in one form or another, is used to model all interfacial dopant flux phenomena. Following is a brief discussion of each of the major cases.

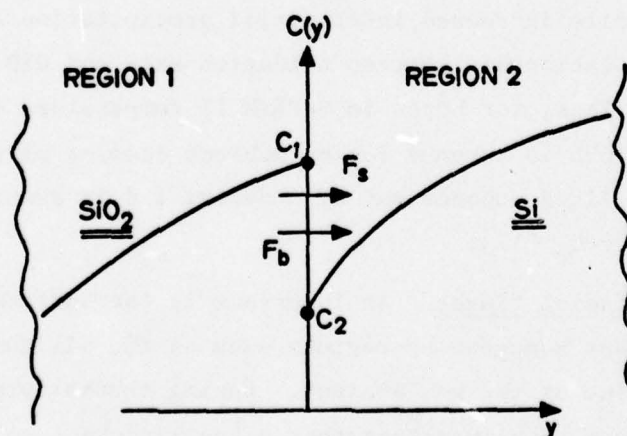


Figure 8 Interfacial flux, F_s , in the silicon-silicon dioxide system. Also shown is the flux induced by the motion of the interface during silicon oxidation.

(a) Evaporation. The mass-transport coefficient becomes the impurity evaporation coefficient which is a function of temperature. The same evaporation coefficient is used for SiO_2 and for silicon. Also, C_1 is assumed zero and $m_{\text{eq}} = 1$.

(b) Chemical deposition. Chemical deposition is simply modeled by assuming (arbitrarily) that $h \rightarrow \infty$, (actually h is set equal to $1 \mu\text{m}/\text{sec}$), $m_{\text{eq}} = 1$ and C_1 equal to either the dopant solid solubility or to any other (user) specified concentration. Thus, the simulated surface concentration of silicon becomes very rapidly equal to C_1 . It is recognized that the model may be overly simplistic but there exist too many different processes by which dopants may be deposited in silicon, making it impractical to attempt to accurately model each of them specifically in a general program like SUPREM.

(c) SiO_2 - Si interfacial flux. Under non-oxidation conditions the SiO_2 -Si interface is stationary and equation (14) is sufficient to model the impurity flux exchanged between the two regions. Unfortunately, there exists practically no characterization of the flux in this stationary system with the exception of the phosphorus doped SiO_2 - Si system (used for silicon doping), which has been carefully explored by Ghoshtagore [22]. In this case h was derived as a singly activated function of temperature, while m_{eq} was assumed infinite. Actually the exact value of m_{eq} would not alter the observed result as long as it is kept large (say > 50).

In the case of a moving interface as in silicon oxidation there also exists a motion-induced interfacial flux resulting from the different dopant concentration, across the interface. This flux denoted by F_b , is given by

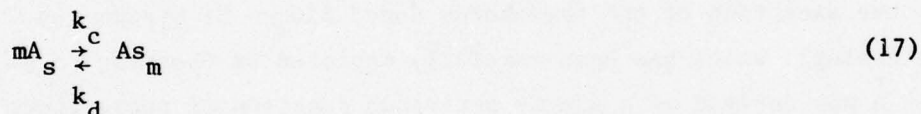
$$F_b = -v_{\text{ox}} (C_1 - \alpha C_2) \quad (16)$$

where $v_{\text{ox}} = dZ_{\text{ox}}/dt$ is the oxide growth rate and α is the ratio of oxidized silicon to resulting oxide thickness (equal to 0.44). F_b is also depicted in Figure 8. Generally this flux competes with the flux F_s . If $h \gg v_{\text{ox}}$ then $C_2 \rightarrow m_{\text{eq}} C_1$ while if $h \ll v_{\text{ox}}$ then $C_1 \rightarrow \alpha C_2$. In all characterizations of the moving interface system to date, the first condition has been implicitly assumed, i.e. that the equilibrium

segregation condition prevails. Thus, in the absence of any meaningful values, h has been arbitrarily set equal to $0.1 \text{ } \mu\text{m}/\text{min}$ in SUPREM II, and thus the condition $h \gg v_{\text{ox}}$ is always satisfied.

Although the exact values of the coefficients are not known at present, the above described modeling of interfacial fluxes is physically more meaningful than the classical model that has been used in SUPREM I. In addition the new model lends itself more to numerical evaluation resulting in substantial improvement of the solution stability.

2.2.5 Generation and loss mechanisms. Almost all dopants may exist in silicon in more than one state particularly when the concentrations are high. Typically one of these states is substitutional and therefore mobile while the other, if present, may be some form of precipitate or cluster which is immobile. Exchange between these two states gives rise to the generation and loss terms in the continuity equation (1) of the mobile species. In SUPREM II a model describing arsenic clustering phenomena [23,24] is included. However, due to lack of similar models, effects of clustering and precipitation on the migration of other impurity atoms has been neglected. The assumed chemical reaction for arsenic is



where m is the number of atoms in a cluster and k_c and k_d the clustering and declustering rate coefficients. Defining the concentration of clustered atoms, C_c , as

$$C_c = C_T - C \quad (18)$$

where C_T is the total concentration and C the substitutional concentration, the conservation equation for C_c may be written as

$$\frac{\partial C_c}{\partial t} = mk_c C^m - k_d C_c = \ell - g \quad (19)$$

where ℓ and g refer to the loss and generation terms in equation (1).

Further, defining the equilibrium clustering coefficient, k_e , by

$$k_e = \left(\frac{k_c}{k_d} \right)^{1/m} \quad (20)$$

We can rewrite equation (19) as

$$\frac{\partial C}{\partial t} = k_d [m(k_e C)^m - C_c] = \ell - g \quad (21)$$

The above equation together with equation (1) are used to describe the thermal migration of arsenic atoms in silicon. The cluster size that gives best fit to recent observed data [24] is $m = 4$ (tetramers). However, there is evidence that clusters of larger size may be involved. The declustering rate coefficient k_d has been adopted from the work of Schwenker et. al. [23]. Under equilibrium conditions (i.e. $\partial C_c / \partial t = 0$) equation (21) yields

$$\frac{C_T}{C} = 1 + 4 k_e^4 C^3 \quad (22)$$

This equation is plotted in Figure 9. It can be seen that clustering imposes a limit to the maximum concentration of substitutional and therefore electrically active, arsenic atoms. This limit is a function of process temperature.

Although the clustering model predicts the formation and dilution of clusters during predeposition and subsequent drive-in, an assumption must be made about the initial cluster concentration when arsenic is implanted. In this case, it is arbitrarily assumed in SUPREM II, that the initial clustered arsenic profile is simply that determined by thermal equilibrium at the annealing temperature, given the known implanted profile of total arsenic atom concentration.

2.3 Thermal Oxidation

The rate of SiO_2 growth on silicon is described in SUPREM II by the well known formula [25]

$$Z_{\text{ox}}^2 + A Z_{\text{ox}} = B(t + \tau) \quad (23)$$

where Z_{ox} is the oxide thickness, t is time and A and B are related to the linear and parabolic growth coefficients K_L and K_P and normalized partial pressure, P_{O_2} , of O_2 by

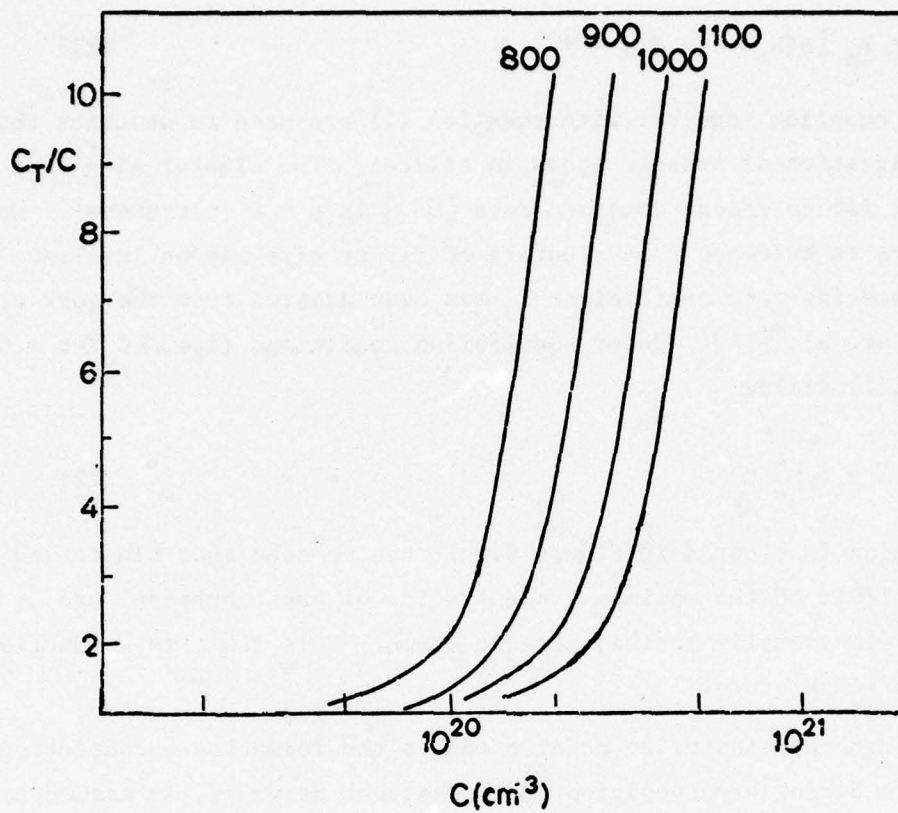


Figure 9 Normalized total arsenic concentration vs the substitutional arsenic concentration, resulting from clustering model, as a function of process temperature, under thermal equilibrium.

$$A = P_{O_2} K_P / K_L$$

$$B = P_{O_2} K_P$$

The parameter τ is related to the initial oxide thickness by

$$\tau = \frac{Z_{ox}^2(t=0) + AZ_{ox}(t=0)}{B} \quad (24)$$

Under relatively low dopant concentration conditions, K_p and K_L depend only on silicon crystal orientation and on the oxidizing ambient, and they are singly activated functions of temperature. All relevant data are given in Appendix 1 together with appropriate references.

It is however well known that under high surface concentration conditions, such as in MOST source and drain or bipolar emitter region, the oxidation rate of silicon is enhanced. A detailed description of the phenomenon has been given by Ho et al. [26]. Briefly, it was found that the linear rate coefficient is substantially enhanced, indicating an enhancement of the surface reaction rate while the parabolic rate, which depends on diffusion of O_2 through SiO_2 is only modestly enhanced. These enhancements are decreased with increasing temperature. In SUPREM II we have incorporated a model proposed by Ho and Plummer [27] which relates quantitatively the enhancement factors for K_L and K_p to the surface dopant concentration. The underlying idea is that the rate of silicon oxidation depends on the lattice vacancy concentration which is affected by the presence of dopant atoms as already discussed in Section 2.2.2.

According to the model, the linear rate coefficient can be written as

$$K_L = K_L^i [1 + \gamma(C^T - 1)] \quad (25)$$

where K_L^i is the intrinsic (i.e. low concentration) coefficient, γ is an experimentally determined parameter given by

$$\gamma = 2.62 \times 10^3 \exp \left[-\frac{1.10 \text{ eV}}{kT} \right] \quad (26)$$

C^T the normalized total vacancy concentration given by

$$C^T = \frac{1 + C^+ \left(\frac{n}{n_i} \right) + C^- \left(\frac{n}{n_i} \right) + C^= \left(\frac{n}{n_i} \right)^2}{1 + C^+ + C^- + C^=} \quad (27)$$

with

$$C^+ = \exp [(E^+ - E_i)/kT] \quad ; \quad E^+ = 0.35 \text{ eV}$$

$$C^- = \exp [(E_i - E^-)/kT] \quad ; \quad E^- = E_g - .57 \text{ eV}$$

$$C^= = \exp [(2E_i - E^- - E^=)/kT]; \quad E^= = E_g - .11 \text{ eV}$$

The above expressions should be recognized as the normalized intrinsic concentrations of vacancies in the three charge states with their corresponding state energies in the silicon bandgap. Finally the silicon energy bandgap, E_g , and intrinsic level, E_i , are given as functions of temperature by

$$E_g(T) = 1.17 - 4.73 \times 10^{-4} [T^2/(T + 636)] \text{ eV}$$

$$E_i(T) = E_g/2 - kT/4$$

For n-type dopants the enhancement of the parabolic oxidation rate has also been obtained by Ho and Plummer [27]. K_p is given as

$$K_p = K_p^i (1 + \delta C_T^{0.22}) \quad (28)$$

where

$$\delta = 9.63 \times 10^{-16} \exp \frac{2.83}{kT} \text{ eV} \quad (29)$$

K_p^i is the intrinsic parabolic rate and C_T is the total n-type dopant atom concentration.

Since during oxidation the impurity surface concentration changes due to diffusion and segregation distribution, the calculated enhanced values of K_L and K_p may generally be time dependent. Thus, rather than using the classical oxide growth equation (22), in SUPREM II an incremental form of the same equation is used, namely

$$\Delta Z_{ox} = \left[\frac{1}{2} - (2Z_{ox} + A) + \sqrt{(2Z_{ox} + A)^2 + 4B\Delta t} \right]$$

Thus, as the simulation time proceeds in small time increments, Δt , and the impurities redistribute in the silicon, the coefficients A and B are obtained from the surface impurity concentrations in each time increment, and from those values the corresponding increment of oxide thickness, ΔZ_{ox} is calculated.

2.4 Silicon Epitaxy

2.4.1 Introduction. Epitaxy is a processing step commonly used in

modern semiconductor fabrication technologies. As with oxide growth, the epitaxial silicon growth step defines a numerical moving boundary problem. The objective of SUPREM II is the simulation of impurity redistribution occurring during this step.

The model for impurity redistribution is vaguely similar to that reported by Langer and Goldstein [28]. Although redistribution caused by diffusion and evaporation is well simulated, front-side autodoping is omitted. Further investigative work is necessary before a reliable front autodoping model can be incorporated in the process simulator.

Backside autodoping has also been neglected to conform with the one-dimensionality imposed on SUPREM II. This, however, should not be a severe limitation because backside autodoping is often avoided either by backside sealing or by the use of ion-implantation on lightly doped substrates. On the other hand, frontside autodoping may be a nonnegligible effect, particularly when lightly doped layers are grown on heavily doped ones.

2.4.2 The model Figure 10 illustrates the epitaxial growth model used in SUPREM. It is assumed that the bulk gas phase has a uniform

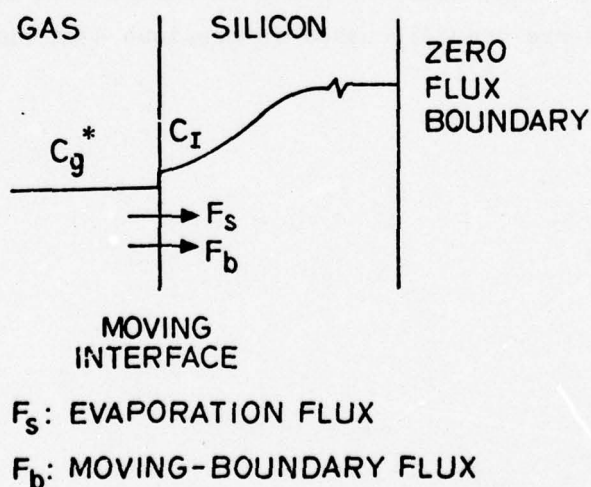


Figure 10 Model for the redistribution of impurities during epitaxial silicon growth.

equivalent concentration of single dopant species, C_{gI}^* . This is a fictitious concentration equal to the desired uniform epi-doping concentration. No real details of the gas phase are considered in SUPREM II.

At the solid gas interface, there exist two flux components, F_s , and F_b as indicated in Figure 10. F_s is an impurity "evaporation" flux,

$$F_s = h(kC_{gI}^* - C_I) \quad (30)$$

where h is the impurity evaporation coefficient, as already discussed in Section 2.2.4. As evaporation flux, we define any impurity flux exchange between the gas and the solid, other than direct moving boundary incorporation; C_I is the impurity concentration at the solid surface, and k is the surface equilibrium segregation coefficient defined as

$$k = \frac{C_I}{C_{gI}^*} \quad (31)$$

The term F_b is a flux induced by the interface motion and can be calculated as in the oxidation case (Section 2.2.4). It is given by

$$F_b = v(C_{gI}^* - C_I) \quad (32)$$

where v is the interface velocity (growth rate)

Within the solid (silicon) body, diffusive flow of impurities is accounted for as has been discussed in previous sections.

3. NUMERICAL IMPLEMENTATION OF PROCESS MODELS

3.1 Introduction

The previous section has described the models of the physical processes that are simulated by SUPREM. In the present section, the numerical implementation of those process models will be discussed with particular emphasis on the discrete formulation of the impurity continuity equation under the moving boundary conditions encountered during silicon oxidation and epitaxy. However, in order to establish a basis for the discussion of this issue, the numerical solution of the continuity equation under stationary conditions will be outlined first.

3.2 Stationary Boundaries

The space over which the impurity continuity equation (2) is to be solved, is partitioned into discrete cells. The impurity concentration, $C(y)$, is evaluated at points (or nodes) lying in the middle of each of the discrete cells. Figure 11 illustrates this space discretization.

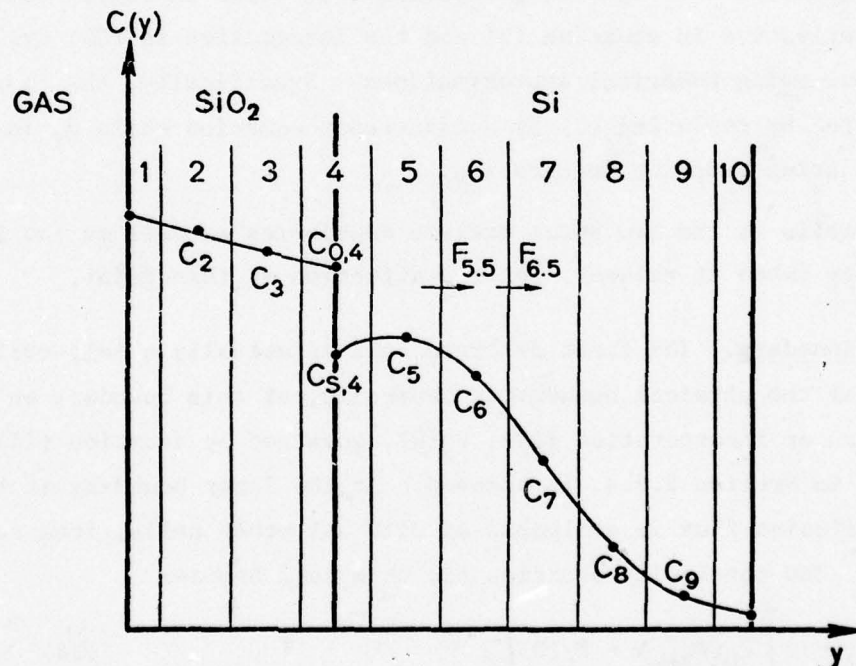


Figure 11 The partitioning of the simulation space into discrete cells. Impurity fluxes across cell boundaries.

For instance, taking cell $i = 6$ as an example, the discrete continuity equation (neglecting generation-loss terms) is written as

$$\frac{d}{dt} Q_6 = - [F_D(y_{6.5}) - F_D(y_{5.5})] \quad (33)$$

where $F_D(y_{6.5})$ and $F_D(y_{5.5})$ are the impurity diffusive fluxes at the right and left-hand boundaries of cell 6, and Q_6 is the impurity content of cell 6. Thus, for the general i th cell not lying at any of the space boundaries, the continuity equation discretized in space becomes

$$\frac{d}{dt} Q_i = - [F_D(y_{i+\frac{1}{2}}) - F_D(y_{i-\frac{1}{2}})] \quad (34)$$

where F_D is evaluated at the cell boundary from equation (5) and Q_i is given by

$$Q_i = \int_{y_{i-\frac{1}{2}}}^{y_{i+\frac{1}{2}}} C_i dy \quad (35)$$

For simplicity we have ignored generation-loss terms in (34). Both the spatial derivative in equation (5) and the integration in (35) are carried out using numerical approximations. Specifically, the flux F_D is evaluated by replacing (5) by a difference equation while Q_i is evaluated using midpoint integration.

The cells at the two space extreme boundaries as well as the SiO_2/Si boundary (when it exists), deserve attention at this point.

(a) Top Boundary. The first discrete cell is actually a half-cell with its node at the physical boundary. Generally, at this boundary an evaporation or incorporation flux, $F_g(0)$, governed by equation (14) as discussed in Section 2.2.4, is assumed. At the inner boundary of this cell a diffusive flux is evaluated as with all other cells, from equation (5). The continuity equation for this cell becomes

$$\frac{d}{dt} Q_1 = - [F_D(y_{1+\frac{1}{2}}) - F_g(0)] \quad (36)$$

(b) Deep Boundary. This boundary usually lies inside the silicon substrate at the point where the simulated space terminates. The last

cell in this end is also a half-cell similar to the first one. However, a reflecting boundary (implied by setting $h = 0$ in equation (14), is assumed here. Because the depth of simulation is user determined, care must be taken to ensure that the presence of a reflecting boundary at that point does not affect the simulation results. On the other hand, this reflecting boundary facilitates significantly the use of SUPREM II in unconventional cases such as Si on sapphire or poly-Si on SiO_2 , where it may be desirable to study the effect of the reflecting deep boundary on impurity redistribution. The continuity equation for this last cell becomes

$$\frac{d}{dt} Q_n = F_D(y_{n-\frac{1}{2}}) \quad (37)$$

(c) SiO_2/Si Interface. Since this interface is an extremum point where impurity concentration must be evaluated it must always lie on a node. This node is shared by two half-cells, the one in SiO_2 and the other in Si. Since the impurity concentration is generally discontinuous across the interface (because of thermodynamic segregation), the interface node contains two different concentrations, one for the oxide half-cell and one for the silicon half-cell. An interfacial flux, F_s , described by equation (14), is assumed to flow between these two cells, while diffusive flux calculated from equation (5) with the appropriate diffusivities for the two materials, is flowing across the other two boundaries. The continuity equation for the two interfacial half-cells becomes

$$\frac{d}{dt} Q_{I,ox} = - [F_s - F_D(y_{I-\frac{1}{2}})] \quad (38)$$

$$\frac{d}{dt} Q_{I,Si} = - [F_D(y_{I+\frac{1}{2}}) - F_s] \quad (39)$$

The established boundary cell equations (36), (37), (38) and (39) together with equation (34) for all other cells constitute a system of equations that describes the temporal evolution of the impurity distribution. Numerically, this evolution is obtained by replacing the time derivative in these equations by a discrete approximation. All the above equations are of the type

$$H_i(t) = \frac{d}{dt} Q_i(t) \quad (40)$$

where $H_i(t)$ denotes in abbreviated form the cell boundary flux difference. Assuming that at time t_0 the concentration distribution is known, the distribution at a future time t_1 may be derived by solving the equation

$$\int_{t_0}^{t_1} H_i(t) dt = Q_i(t_1) - Q_i(t_0) \quad (41)$$

Various methods exist for performing this integration numerically. The method used in SUPREM II is first order implicit, i.e. it assumes that during the time interval $(t_1 - t_0)$, $H_i(t) = H_i(t_1)$. Then the above equation becomes

$$H_i(t_1) = [Q_i(t_1) - Q_i(t_0)] / (t_1 - t_0) \quad (42)$$

Now, there are as many equations of the form given above, as the number of discrete space cells. Also, since for each cell the function H_i , is evaluated at t_1 (i.e. at the future time), it involves not only the unknown cell concentration $C_i(t_1)$ but also the two neighboring cell concentrations $C_{i\pm 1}(t_1)$. Thus, the resulting equations are mutually coupled and form a system with a tridiagonal determinant. This system of equations is solved successively in small (simulated) time increments by means of gaussian elimination. Also, since the system may be non-linear due to the dependence of diffusivity on impurity concentrations, Newton-Raphson iterations of the solution are performed until convergence of the results (concentrations) is achieved.

3.3 Moving Boundary - SiO₂/Si

When silicon is oxidized the interface between SiO₂ and Si moves into the silicon and the oxide layer expands with a velocity $v_{ox}(t)$ given by

$$v_{ox}(t) = \frac{dz_{ox}(t)}{dt} \quad (43)$$

where z_{ox} is determined as discussed in Section 2.3. Under these conditions a moving boundary induced impurity flux, F_b , given by equation (16)

also flows across the interface.

The presence of the moving boundary complicates the numerical formulation of the continuity equation in two ways. Firstly, because of the non-unity volumetric ratio of Si to SiO_2 ($\alpha = 0.44$), there is expansion of the discrete volume cells as they become part of the SiO_2 . Figure 12 illustrates this effect. Thus, for the cells around the interface, volume is a function of time and the integration boundaries of equation (35) change between times t_0 and t_1 . Secondly, the existence of the two interfacial fluxes F_s and F_b creates a jump discontinuity in the impurity flux, that propagates through space during oxidation. Referring to Figure 13 the flux across the interface from time t_0 to t_1 can be considered as a superposition of two separate processes. The first process assumes that the interface moves instantaneously (at t_0^+), to its new node and that F_s flows for the time interval (t_0, t_1) . The second process consists of the redistribution of the impurity contents of the two SiO_2 cells nearest the interface due to the moving boundary flux F_b that flows across the boundary of these two cells.

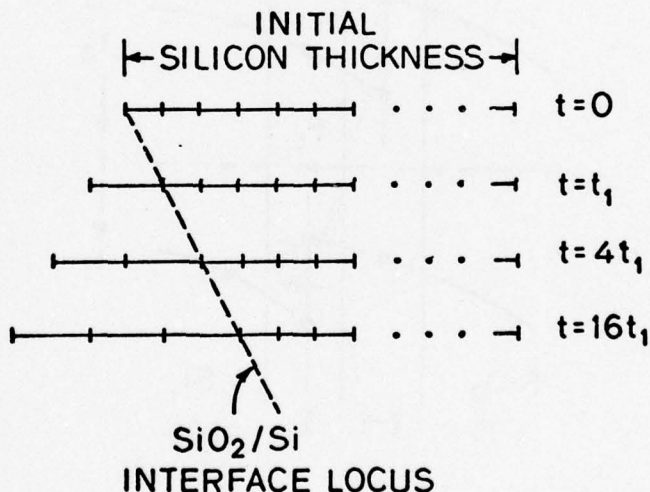


Figure 12 Relationship of SiO_2 and Si volumes when silicon is oxidized at four different times. Here the oxidation rate is assumed purely parabolic. The tick marks identify cell boundaries.

Numerically assuming that the discontinuity occurs in the immediate vicinity of the i th cell at a time t in the interval (t_0, t_1) , the first order implicit approximation to the integral equation (41) yields

$$H_i(t_1) \pm \frac{t_1 - t}{t_1 - t_0} F_b(t_1) = [Q_i(t_1) - Q_i(t_0)] / (t_1 - t_0) \quad (44)$$

Referring to Figure 13, i may be equal to I or to $I-1$, where I identifies the interface node. The $+$ sign is used when the equation represents the continuity in the interfacial cell I in SiO_2 and the $-$ sign when the continuity in cell $I-1$, also in SiO_2 , is represented.

To complete this discussion, it remains now to outline the interrelation of time and space discretization that arises from the consideration of the moving boundary. Given the constraints that the interface must always lie on a node and that the number of oxide nodes may increase by at most one node in any time step, two basic possibilities for advancement of the interface exist in SUPREM II, depending on the oxidation rate

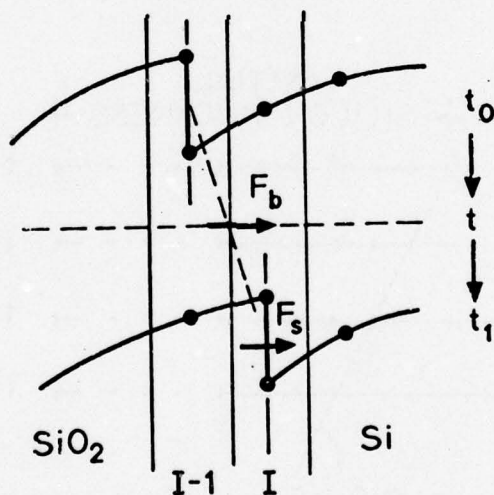


Figure 13 Interfacial cells and moving boundary flux at two increments of time. For simplicity the volumetric ratio, α , is assumed unity.

which is typically a quadratic function of time. These two possibilities are illustrated in Figure 14. Note that the figure has been drawn assuming $\alpha = 1$ for clarity. In Figure 14(a) the number of oxide nodes increases by one, while in 14(b) it remains fixed. In the first case, (a), the interface crosses the left hand boundary of the cell that contains the interface in time t_1 , while in the second case, (b), it does not cross any boundary. When case (a) arises, equation (44) must be used in the two cells that share the crossed boundary while in case (b) the cells in the neighborhood of the interface see no special boundary flux i.e. equation (42) is valid just as in all other cells. Of course, in both cases the fact that the volumes of the two cells change in the interval (t_0, t_1) must be accounted for, in establishing the cell impurity content. Thus, as already mentioned the limits of integration in equation (35) are time dependent for the two cells in the interface neighborhood.

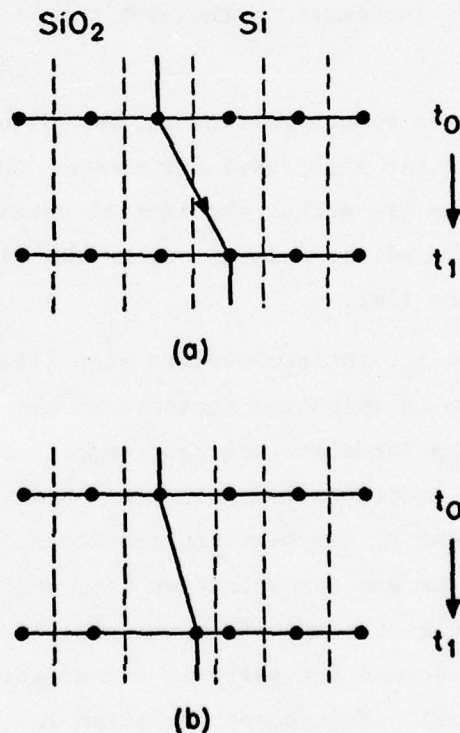


Figure 14 Examples of interface motion (a) when the number of oxide nodes increases by one and (b) when the number does not increase. In case (a) the interface crosses the cell boundary while in (b) it does not. For simplicity $\alpha = 1$ has been assumed.

3.4 Moving Boundary - Epitaxy

As with oxidation-diffusion, discussed in Section 3.3, the epitaxial growth-diffusion algorithm has been derived from the impurity conservation equation [Eq. (1)]. Special treatment of fluxes is necessary only at the moving/gas solid interface. Again the algorithmic constrain is imposed -- the interface must always lie on a spatial grid node and, during any simulated time increment t , no more than one new node of solid can be generated. This is illustrated in Figure 15. The solid vertical lines identify the gas/solid interface, and the broken lines delineate the discrete subcell boundaries across which the fluxes flow. The concentration in each subcell is considered uniform with value equal to the concentration at the grid node.

The numerical method used for the solution of the conservation equation is implicit, first order in time and uses midpoint integration in space. The procedure for the solution of the resulting system of equations from one time increment to the next can be best understood by referring to Figure 15.

- (a) At time t_0 , the concentrations in the solid and the gas (near the interface) are known. These concentrations are either the initial conditions or the results of the solution up to the simulated time t_0 (Figure 15a).
- (b) Still at time t_0 , an intermediate step (Figure 15b) is taken at which the contents of the two cells near the interface are rearranged. Specifically, the concentration at the new node, $i-1$, to be added during the next time increment Δt , is fixed at the gas concentration C_{gI}^* , and the concentration at the interface node, i , is modified to account for particle conservation in the i th subcell. The second operation is necessary because one nodal concentration value must be used to account for the current in each

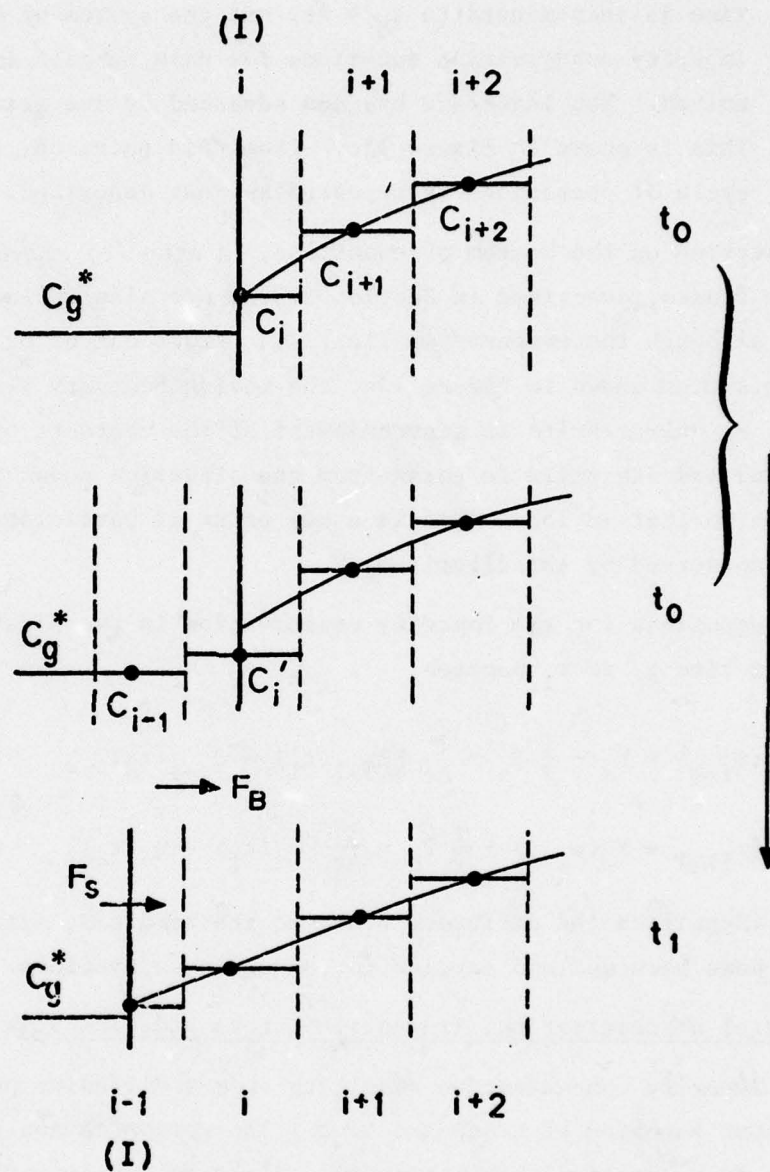


Figure 15 Motion of the silicon/gas interface in the discrete space, during epitaxial silicon growth. For explanation see text.

subcell. The results of this intermediate step serve now as initial conditions for the next time increment.

- (c) Time is incremented to $t_0 + \Delta t$, and the system of coupled impurity conservation equations for each subcell is solved. The interface has now advanced by one grid node. This is shown in Figure 15c. From this point on, the cycle of operations is repeated as just described.

In setting up the system of equations, in step (c) above, the two interface fluxes, described in Section 3.3.2, are also included; however, although the evaporation flux, F_s , flows out of or into the composite system shown in Figure 15c, the moving boundary flux F_b does not; F_b only results in rearrangement of the contents of the $(i-1)$ th and i th cells in going from the situation shown in Figure 15b to that in 15c. This is a key point if particles are to be fully conserved by the algorithm.

The equations for the impurity conservation in the first two cells from time t_0 to t_1 becomes

$$-F_D(y_{i-\frac{1}{2}}) + F_s - \frac{1}{2} F_b = \frac{1}{\Delta t} [Q_{i-1}(t_1) - Q_{i-1}(t_0)] \quad (45)$$

$$-F_D(y_{i+\frac{1}{2}}) + F_D(y_{i-\frac{1}{2}}) + \frac{1}{2} F_b = \frac{1}{\Delta t} [Q_i(t_1) - Q_i(t_0)] \quad (46)$$

where F_D identifies the diffusive flux and the remaining symbols and indexing have been defined earlier in the previous sections.

3.5 Spatial Discretization, Truncation Errors and Time Step Generation

The impurity concentration resulting from a diffusion process is a continuous function of space and time. The concentration profile resulting from numerical simulation is a discrete approximation both in space and time, to this continuous function. This space and time discretization naturally leads to so-called truncation errors of the numerical solution of the continuity equation. These errors are small provided the space and time intervals are small.

In SUPREM II the maximum number of discrete space intervals is fixed to 400 and thus there is a limitation imposed to the smallest space increment, Δy , that can be used. However it has been found through practice that spacial steps of order 100\AA provide accurate results under most circumstances. Clearly there exists a trade-off between computation (CPU) time necessary for a particular simulation and spacial discretization errors. It is very hard to derive general forms that would rigorously satisfy specific trade-off goals, particularly since profiles of different shapes may coexist in any simulation. A good rule of thumb for selecting Δy maybe that it be fine enough to adequately represent the sharpest final profile of the simulation.

Generally, as time progresses during a process involving diffusion, the profiles tend to become less steep, and thus the rate of change of the content of each discrete subcell diminishes. It is reasonable to assume that temporal discretization errors for a particular discrete space would be proportional to the rate of change of the profile, i.e. to the rate of change of impurity content of each subcell. Thus, if in the interest of CPU time economy, temporal truncation errors are to be kept rather constant during a simulation, the time steps should become longer as simulation time elapses. This scheme has been adopted in SUPREM II where the time steps (which are built-in to the program), increase parabolically with time starting from a small value of about half a minute. Again through practice it has been found that this scheme provides accurate results under most process simulation conditions.

Finally, it should be mentioned here that a latency feature exists in SUPREM II, that can significantly reduce the CPU time of simulations. The basic idea is that impurity concentrations below 10^{13} cm^{-3} (this is arbitrary), are not physically significant and thus need not be processed. An algorithm is built-in to the program that keeps track of the length of simulation space for each impurity species and increases it as the profiles spread out by diffusion. Thus, the number of spacial points over which the continuity equation is numerically solved, is always optimum and is controlled by direct feedback from the actual profile being processed.

4. CALCULATION OF ELECTRICAL PROPERTIES

4.1 Introduction

The previous sections have described the models and their numerical implementation used in SUPREM II to obtain the impurity profiles resulting from simulated processes. Ideally, these profiles together with some lateral geometry information would serve as an input to a device analysis program that may calculate electrical parameters and predict the behavior of devices under development, thus completing the cycle of device computer design. However, a lot of insight into the performance of devices and circuits is often gained from simple electrical parameter calculations. For this reason SUPREM II incorporates the calculation of layer or sheet resistance and of MOS threshold voltage. Following is a discussion of the implementation of these two calculations. In this section the symbol $N(y)$ is used to denote the net carrier concentration under quasi-neutrality conditions. It is defined as $N(y) = C_A(y) - C_D(y)$ where C stands for atomic impurity concentration and the subscripts A and D for acceptor and donor impurity type.

4.2 Sheet Resistance

Layer resistance is calculated as the reciprocal of the average conductivity of the layer given by the equation

$$\frac{1}{\rho_0} = \bar{\sigma} = \frac{q}{y_2 - y_1} \int_{y_1}^{y_2} \mu(C) N(y) dy \quad (47)$$

where y_1, y_2 define the boundaries of the layer (measured from the top silicon surface), q is the elementary charge, $N(y)$ the net carrier concentration defined above and $\mu(C)$ the appropriate carrier mobility which is a function of total impurity concentration [20]. The net carrier concentration is calculated by assuming total impurity electrical activity except in the case of arsenic where only the unclustered atoms are assumed to contribute electrons and in the case of phosphorus where the electron concentration, n , is related to the atomic impurity concentration, C , by the expression [15]

$$C = n + 2.04 \times 10^{-41} n^3 \quad (48)$$

Both of the above exceptional cases are important for heavy doping conditions.

Sheet resistance is calculated in SUPREM II for all layers of individual type resulting from a process simulation. For example, in the case of simulation resulting into an npn layer structure three sheet resistances are calculated, namely, (a) of the n-layer extending from the silicon surface to the np junction (b) of the p-layer extending from the first (np) to the second (pn) junction and (c) of the n-layer extending from the second (pn) junction to the end of the simulated space. The sheet resistance of the layer bounded by the end of the space may or may not be of physical significance, depending on the particular process that is simulated. Also, the sheet resistance of the middle layer in the above example which could be interpreted as a pinched base resistance may well be an underestimate since depletion regions are not considered in the calculations.

4.3 MOS Threshold Voltage

The calculation of MOS threshold voltage, V_T , is implemented in SUPREM II based on the full depletion approximation and the assumption of quasi-neutral impurity profiles [28]. Figure 16 shows a typical p-type implanted impurity profile. It is assumed that all the carriers are depleted for $0 \leq x \leq x_d$. The threshold voltage is then calculated from

$$V_T = V_{FB} + \psi_s + V_B \quad (49)$$

where V_{FB} is the flat band voltage given by

$$V_{FB} = \phi_{MS} - q N_{ss} / C_{ox} \quad (50)$$

with ϕ_{MS} the gate-semiconductor contact potential dependent on the gate material and on the channel surface doping, N_{ss} the oxide interface charge density and C_{ox} the oxide capacitance per unit area.

ψ_s is the surface potential under strong inversion conditions given by [28]

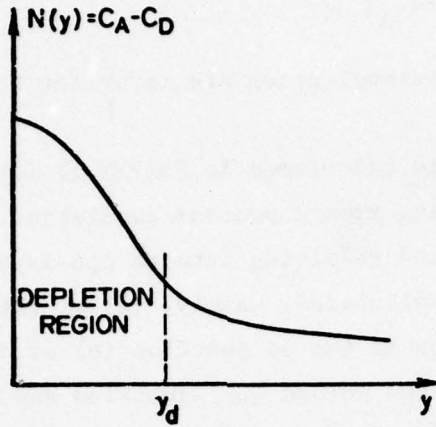


Figure 16 A typical p-type profile resulting from boron ion-implantation. $N(x)$ is the hole distribution under quasi-neutrality conditions.

$$\psi_s = \pm \frac{kT}{q} \ln \left[\frac{N_b N(y_d)}{n_i^2} \right] \quad (51)$$

where N_b is the carrier concentration at the bulk contact and $N(y_d)$ the same at the edge of the depletion region. N_b may be the surface concentration, the substrate concentration or an arbitrary user determined concentration. Obviously N_b and $N(y_d)$ must be of the same type. Details on the specifications of C_b is given in Appendix 1. The positive sign refers to p-type and the opposite to n-type impurities.

Finally, V_B is the silicon bulk voltage given by

$$V_B = \frac{q}{C_{ox}} \int_0^{y_d} N(y) dy \quad (52)$$

The one unknown in the above equations is the depletion region width y_d . This is determined by solving the Poisson equation using the full depletion approximation.

$$\frac{d^2 \psi}{dx^2} = - \frac{q}{\epsilon_s} (C_D(y) - C_A(y)) = \frac{q}{\epsilon_s} N(y) \quad (53)$$

Double integration of this equation and use of the appropriate boundary conditions yields

$$\psi_s = \frac{q}{\epsilon_s} \left\{ y_d \int_0^{y_d} N(y) dy - \iint_0^{y_d} N(y) dy^2 \right\} \quad (54)$$

Thus, y_d is determined by numerical solution of the non-linear system of equations (51) and (54).

Within the accuracy limitations imposed by the assumptions used here, V_T can be calculated for any arbitrary impurity profile. The vertical profile under the gate does not have to be of a single doping type. Thus, a junction may exist within the depletion region as is often the case with implanted channel and depletion mode devices. The one important consideration is that the doping type at the bulk contact be the same as that at the edge of the depletion region. If the profiles are such that this is not satisfied, no threshold voltage can be calculated.

5. SUPREM II DATA STRUCTURE

5.1 General Information

The SUPREM II data structure is divided into five main blocks. The first block is made up of six, 450 word, real arrays. The first three of these arrays contain information about the impurities being processed in the process under simulation. The discretized impurity profiles are stored in the first 401 words of each array, followed by one word specifying the impurity element, nine words containing spatial grid information about the profile, (see Figure on page 55) and the rest containing the physical constants pertaining to redistribution of the impurity. The fourth of the six arrays is reserved for storing the total arsenic distribution (including clusters), while the fifth is a general working array. The sixth of the arrays in this block is used to hold the 400 point spatial matrix indicating the distance between each of the points in the profiles of the previous arrays. The last fifty points of the sixth array contain current step parameters such as temperature, time, ambient, etc.

The second block is made up of three arrays, one of type logical, one of type integer and one of type real. These arrays contain information regulating the type and quantity of input and output, along with some grid and substrate information that is not normally variable from step to step. In addition some temporary grid pointers used when oxidizing or growing epitaxial silicon are also stored in the second block.

The third block consists of arrays containing model card parameters as described in the SUPREM II user's manual (Appendix 1). The arrays are initialized to the internal default values when the substrate card is read-in and are modified by the occurrence of the model cards in the input deck. When a model card is referenced in a step card, the model parameters are read from the appropriate array in this block.

The fourth block is made up of four 410 word arrays which are used as working arrays by various routines throughout the program. The fifth block is reserved for future implementation of an optimization routine.

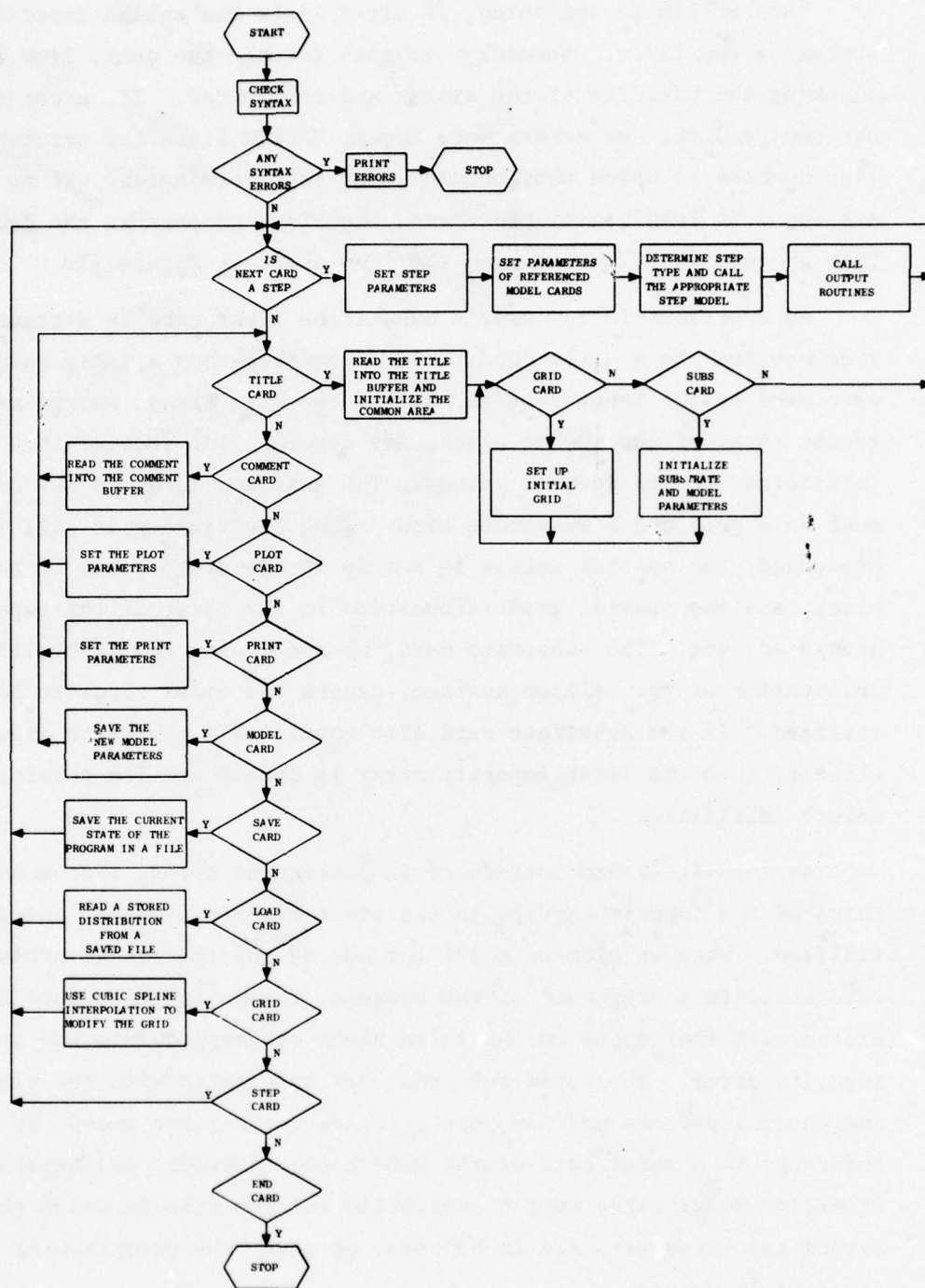


Figure 17 Flowchart of SUPREM II program.

When SUPREM is initiated, it first lists the entire input deck, numbering the lines. Secondly, it goes through the deck, line by line, checking the validity of the syntax and card order. If, after checking the entire deck, any errors were found, SUPREM lists the errors and the line numbers in which they occurred, and then terminates. If no errors are found it then begins processing the first process in the deck. This process is illustrated in the flow chart of Figure 17.

As described in the user's manual the first card in a processing sequence must be a title card, this is because when a title card is processed by the input routine, all of the data arrays described above, except those of the second block, are zeroed. The second block is initialized to its default values. The next two cards in the sequence must be a grid and a substrate card. When the first grid card is processed, the spatial matrix is set up in the sixth array of the first block, and the spatial grid information in the first of the impurity arrays are set. The substrate card, by specifying the crystalline orientation of the silicon surface, causes the model cards to be initialized. If the substrate card also specifies a substrate impurity element, then the first impurity array is opened and its physical parameters initialized.

As impurities are introduced in subsequent steps, the second and third of the impurity arrays in the first block are opened and initialized. When an element model for one of the impurities present is referenced in a step card of the process, the parameter values associated with that model in the third block are mapped into the appropriate impurity array. The parameters that are associated with the element, and special purpose models, once set, are not changed except by a later reference to a model card of the same type. However, epitaxial and oxidation model cards must be specified at each step in which their associated parameters are to be used, or else the program will use its default values.

5.2 Program Segmentation

Following is a list of the SUPREM II main program and segments together with the routines that they use. A brief description of each

of the routines is included in the source code and thus will not be given here. The program structure reflected in this section is the original one, developed on a Hewlett-Packard 2100 minicomputer under DOS-III operating system. Although this segmentation is not a unique solution it can serve as guide to those users of SUPREM II that may wish to use the program on small machines.

SUPREM MAIN AND SEGMENTS

SUPREM Main

SUPRM STPRC OPTIM FUNC

Segment SUSYN

SUSYN GETLN ERSET GDSYN SBSYN PLSYN PRSYN SLSYN MDSYN STSYN
OPSYN RLSY STOSY ISCOM PARSE LGTOP GETRL IGTEL MODNN STPTP
PARTP IFTYP ITYPE

Segment SUINP

SUINP COMST ERSET PLTST PRNST MODST STPSV OPTST RSLTS STOPS
GETLN PARSE INITE ISCOM LGTOP GETRL IGTEL MODNN STPTP PARTP
IFTYP ITYPE

Segment TGSIN

TGSIN GETLN FGRID SUBS ISCOM ERSET PARSE BNDRS INITE OXINT
LGTOP GETRL IGTEL MODNN STPTP PARTP IFTYP TYPE

Segment SVLDF

SVLDF PARSE SAVFL LODFL ERSET LGTOP GETLN ISCOM GETRL IGTEL
MODNN STPTP PARTP IFTYP ITYPE

Segment GRDNW

GRDNW PARSE ERSET CGRID LGTOP GETLN ISCOM GETRL IGTEL MODNN
STPTP PARTP IFTYP BNDRS SPLIN SEVAL ITYPE

Segment STPST

STPST PARSE ERSET INITE MODIN OXIDI EPTAX LGTOP GETLN ISCOM
GETRL IGTEL MODNN STPTP PARTP IFTYP OXINT SOLUB ITYPE

Segment IMPLN

IMPLN ERSET QDIMP IPLNT GAUSN IMPRS PRSON TRAPZ SPLIN SEVAL

Segment DIFOX

DIFOX PREQ OXTHI TIMOX SITHI DIFPR OXDEP INTRP COEF1 SOLVE
PRINT UPREC ACTIVE DFPB DFFY PREC

Segment DIFEP

DIFEP GRIEP PREQ CFEPI SLVEP PREPI UPREC SPLIN SEVAL DFFY

Segment OPTIO

OPTIO

Segment OPTPR

OPTPR DJAC LNEQS LUDEC LUELM

Segment OUTP1

OUTP1 ACTIVE SHEET VTHRS QDINT EOUTP WRTQD TRAPZ SPLIN INSPL

Segment OUTP2

OUTP2 PROUT PLTLP EOUTP PRVAL SPLIN SEVAL

Segment SUERR

SUERR

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APPENDIX I

SUPREM-II USERS MANUAL

STEPHEN E. HANSEN
D. A. ANTONIADIS
R. W. DUTTON

JULY 04, 1978

FOR THE 0-02 VERSION OPERATING ON
AN IBM 370/168 USING THE FORTRAN-4 LEVEL H
COMPILER

SUPREM-II INPUT FORMAT

THE INPUT PARAMETERS FOR SUPREM ARE SPECIFIED BY A SEQUENCE OF CARDS OR LINES IN A DATA FILE, EACH OF WHICH BELONGS TO ONE OF THE FOLLOWING CARD OR LINE TYPES.

INITIALIZATION -----	INPUT/OUTPUT -----	PROCESS/MODEL -----
TITLE	PRINT	STEP
COMMENT	PLOT	MODEL
GRID	SAVE	
SUBSTRATE	LOAD	
END		

EACH CARD CONSISTS OF ONE OF THE ABOVE CARD TYPE IDENTIFIERS FOLLOWED BY EITHER A PARAMETER LIST OR A CHARACTER STRING (OF WHICH ONLY THE FIRST FOUR CHARACTERS ARE SIGNIFICANT). THE PARAMETER LIST OR CHARACTER STRING IS SEPARATED FROM THE CARD TYPE IDENTIFIER BY EITHER A COMMA OR ONE OR MORE BLANKS. ONLY THE FIRST 72 COLUMNS OF A LINE ARE READ BY SUPREM'S INPUT PROCESSOR. IF NOT ALL OF THE PARAMETERS OF A CARD'S PARAMETER LIST WILL FIT ONE ONE LINE, THEY MAY BE PLACED ON THE FOLLOWING LINE IF A PLUS (+) IS USED AS THE FIRST NON-BLANK CHARACTER OF THAT LINE. CARD TYPES THAT USE A CHARACTER STRING INSTEAD OF A PARAMETER LIST MAY NOT HAVE A CONTINUATION LINE. ALL BLANK LINES ARE IGNORED.

THE CARD TYPES THAT HAVE A CHARACTER STRING INSTEAD OF A PARAMETER LIST ARE TITLE, COMMENT, STOP AND END. THE STRINGS IN ANY TITLE OR COMMENT CARDS ARE USED BY THE OUTPUT ROUTINES, WHILE TEXT IN STOP OR END CARDS IS IGNORED. THE PARAMETERS IN THOSE CARDS WHICH USE A PARAMETER LIST ARE SPECIFIED BY A PARAMETER NAME TO WHICH A VALUE IS EQUATED (I.E. <NAME>=<VALUE>). THE PARAMETER/VALUE PAIRS MAY OCCUR IN ANY ORDER WITHIN THE LIST, SEPARATED FROM EACH OTHER BY COMMAS. ANY BLANKS OR SPACES WITHIN THE LIST ARE IGNORED.

THE VALUES ASSIGNED TO THE VARIOUS PARAMETERS MAY BE OF SEVERAL DIFFERENT TYPES (I.E. NUMERICAL, LOGICAL, ETC.). IN THE CARD TYPE DESCRIPTIONS ON THE FOLLOWING PAGES, THE TYPE OF VALUE THAT IS ASSIGNED TO A PARAMETER IS INDICATED BY ONE OF THE FOLLOWING SYMBOLS.

SYMBOL	TYPE	EXAMPLE OR (DESCRIPTION)
<N>	NUMERICAL	10. , 2 , 1.28E-14 , 350.236
<L>	LOGICAL	T , TRUE , Y , YES , F , FALSE , N , NO
<E>	ELEMENT	B (BORON), P (PHOSPHORUS), SB (ANTIMONY), AS (ARSENIC)
<S>	STEP TYPE	(SEE STEP CARD DESCRIPTION)
<M>	MODEL TYPE	(SEE MODEL CARD DESCRIPTION)
<P>	PARAMETER NAME	(THE NAME OF A OPTIMIZING OR RESULT PARAMETER)
<FT>	FILE TYPE	A , ASCII , B , BINARY

ALL LENGTHS, AREAS, AND VOLUMES ARE GIVEN IN MICRON BASED UNITS, EXCEPT FOR IMPURITY CONCENTRATIONS, WHICH ARE GIVEN IN ATOMS/CUBIC CENTIMETER, AND IMPLANT DOSES GIVEN IN ATOMS/SQUARE CENTIMETER. TIMES ARE ALWAYS GIVEN IN MINUTES AND SO VELOCITIES ARE IN MICRONS/MINUTE AND DIFFUSIVITIES ARE IN MICRONS SQUARED/MINUTE.

FOLLOWING IS A DESCRIPTION OF EACH CARD TYPE AND ITS ASSOCIATED PARAMETERS. IN THIS DESCRIPTION OPTIONAL PARAMETERS OR PARAMETER GROUPS ARE ENCLOSED BY SQUARE BRACKETS, []. WHERE ONE OF A LIST OF PARAMETERS OR PARAMETER GROUPS MUST BE CHOSEN, THE CHOICES ARE ENCLOSED BY ROUND BRACKETS, (), SEPARATED BY THE WORD "OR".

A. INITIALIZATION CARDS

TITLE CARD

THE TITLE CARD SPECIFIES THE CHARACTER STRING USED BY THE PRINT AND PLOT ROUTINES TO LABEL THE OUTPUT. THE TITLE CARD ALSO CAUSES THE INITIALIZATION OF MANY OF THE PROGRAM'S DATA BUFFERS AND SO IT MUST BE THE FIRST CARD IN ANY PROCESSING SEQUENCE. IF SEVERAL PROCESSES ARE TO BE RUN, THEY MAY BE PLACED IN THE SAME INPUT FILE, SEPARATED BY THEIR TITLE CARDS.

TITLE [<CHARACTER STRING>]

COMMENT CARD

COMMENT CARDS CAN BE PLACED AT ANY POINT IN A PROCESSING SEQUENCE AFTER THE INITIAL TITLE, GRID AND SUBSTRATE CARDS. THE CHARACTER STRING SPECIFIED IN THE LAST COMMENT CARD BEFORE A STEP CARD IS USED BY THE PRINT AND PLOT ROUTINES TO LABEL THE OUTPUT.

COMMENT [<CHARACTER STRING>]

END CARD

THE END CARD IS USED TO TERMINATE THE PROGRAM AND SO MUST BE THE LAST CARD IN THE INPUT FILE OR CARD DECK.

END [<CHARACTER STRING>]

GRID CARD -----

THE SILICON WAFER IN SUPREM IS REPRESENTED BY UP TO 400 POINTS SPACED ALONG AN AXIS PERPENDICULAR TO ITS THE SURFACE. THESE POINTS ARE DIVIDED AMONG THREE REGIONS, THE GRID SPACING, (DISTANCE BETWEEN ADJACENT POINTS) IS UNIFORM WITHIN EACH REGION BUT USUALLY DIFFERS FROM REGION TO REGION.

THE FIRST REGION IS THE ONE REPRESENTING THE OXIDE. THIS REGION IS ALLOCATED FROM TEN TO FIFTY POINTS IF AN OXIDE LAYER EXISTS AND ZERO POINTS IF NO OXIDE EXISTS. THE GRID SPACING AND THE ACTUAL NUMBER OF POINTS USED THIS REGION ARE DETERMINED BY THE PROGRAM.

THE SILICON DISTRIBUTION IS STORED IN THE NEXT TWO REGIONS. THESE REGIONS DIFFER ONLY IN THEIR GRID SPACINGS, THE SECOND REGION HAVING A GRID SPACING AT LEAST TWICE THAT OF THE FIRST. THE GRID SPACING IN THE FIRST SILICON REGION IS DETERMINED BY THE GRID CARD'S DYSI PARAMETER, ITS BOUN- DRIES EXTEND FROM THE SILICON SURFACE TO A DEPTH SPECIFIED THE GRID CARD'S DPTH PARAMETER. (THE SILICON SURFACE IS EITHER THE OXIDE/SILICON INTERFACE OR THE SURFACE OF THE WAFER IF NO OXIDE IS PRESENT). THE GRID CARD'S YMAX PARAMETER SPECIFIES THE MAXIMUM SILICON DEPTH REPRESENTED AND SO THE BOUN- DRIES OF THE SECOND SILICON REGION ARE AT DPTH, THE END OF THE FIRST SILICON REGION, AND AT YMAX, THE END OF THE SILICON. THE PROGRAM WILL TRY TO USE A GRID SPACING OF OF TWO TIMES DYSI IN THE SECOND SILICON REGION, BUT IF THIS WOULD CAUSE THE NUMBER OF GRID POINTS TO EXCEED THE 400 POINT MAXIMUM, THE PROGRAM WILL INCREASE THE GRID SPACING TO FIT THE NUMBER OF POINTS AVAILABLE.

THE REASON FOR HAVING TWO REGIONS IN THE SILICON IS THAT INCLUDING A DEEP STRUCTURE, SUCH AS A BURIED COLLECTOR, MAY REQUIRE A GRID SPACING THAT IS TOO COARSE TO ACCURATELY REPRESENT A STEEP OR NARROW PROFILE NEAR THE SURFACE, SUCH AS AN ION IMPLANT. IN THIS CASE THE FIRST SILICON REGION, WHO'S GRID SPACING CAN BE SPECIFIED BY THE USER THRU THE DYSI PARAMETER, IS EXTENDED TO COVER THE STEEP OR NARROW PART OF THE DISTRIBUTION. IN ALL BUT A FEW CASES, GRID SPACINGS OF LESS THAN 0.01 MICRONS IN THIS REGION ARE UNNECESSARY. IN FACT, GRID SPACINGS OF 0.02 AND 0.03 ARE OFTEN MORE THAN ADEQUATE.

IF POSSIBLE, THE PROGRAM WILL USE LESS THAN THE MAXIMUM NUMBER OF GRID POINTS FOR THE DISTRIBUTION, AND SINCE THE TIME OF CALCULATION AND OUTPUT IS DEPENDENT UPON THE NUMBER OF POINTS IN THE DISTRIBUTION, THE USER SHOULD CHOOSE THE GRID PARAMETERS SO THAT THE MINIMUM NUMBER OF POINTS ARE USED.

GRID CARDS MAY APPEAR ANYWHERE IN A PROCESSING SEQUENCE. THIS ALLOWS THE USER TO MODIFY THE GRID SPACINGS AND BOUNRIES IF NECESSARY TO KEEP SUF- FICIENT ACCURACY WHILE MINIMIZING THE TIME OF CALCULATION. WHILE GRID CARDS MAY APPEAR ANYWHERE, AT LEAST ONE MUST APPEAR EITHER IMMEDIATELY AFTER THE TITLE OR SUBSTRATE CARDS IN ORDER TO INITIALIZE THE GRID. THE TOTAL DEPTH OF THE SIMULATION SPECIFIED BY YMAX, MAY BE EXTENDED BY LATER GRID CARDS. SILICON ADDED IN THIS WAY HAS A CONCENTRATION IN THE ADDED SILICON THAT IS EQUAL TO THE CONCENTRATION IN THE LAST POINT IN THE ORIGINAL SILICON.

```

I<-SURFACE  I<-INTERFACE
I           I<-----DPTH----->I
I           I<-----YMAX----->I           I
I   07      I   DYSI      I   GREATER THAN OR EQUAL TO 2*DYSI  I           I
I-----I-----I-----I-----I-----I-----I-----I
I   OXIDE   I   SI REGION 1 I   SI REGION 2                       I           I
I<-----400 POINTS----->I

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GRID (DYSI=<N>) [,DPTH=<N>] [,YMAX=<N>]

DYSI : SPACING BETWEEN GRID POINTS IN MICRONS IN THE REGION FROM THE SILICON SURFACE TO THE DEPTH SPECIFIED BY DPTH. DEFAULT VALUE = 0.01

DPTH : THE DEPTH IN MICRONS OF THE SILICON REGION THAT BEGINS AT THE SILICON SURFACE AND WHOSE GRID SPACING IS GIVEN BY DYSI. DEFAULT VALUE = 0.01

YMAX : THE MAXIMUM CALCULATION THICKNESS OF THE SILICON IN MICRONS. THERE IS NO DEFAULT VALUE. THIS PARAMETER IS REQUIRED ON THE FIRST GRID CARD IN THE PROCESSING SEQUENCE AND CAN BE EXTENDED SUBSEQUENTLY. GRID ALLOCATIONS BETWEEN DPTH AND YMAX ARE EITHER 2*DYSI OR THE MINIMUM VALUE NEEDED TO FIT THE 400 POINT LIMIT.

SUBSTRATE CARD

THE SUBSTRATE CARD PROVIDES THE PROGRAM WITH INFORMATION ABOUT THE SUBSTRATE, SUCH AS THE CRYSTALLINE ORIENTATION AND ANY INITIAL UNIFORM IMPURITY CONCENTRATION. SINCE THIS INFORMATION IS NEEDED BEFORE ANY PROCESSING CAN BEGIN, SUBSTRATE CARDS MUST APPEAR IMMEDIATELY AFTER EITHER THE TITLE OR INITIAL GRID CARD. SUPREM WILL CURRENTLY HANDLE ONLY SILICON SUBSTRATES WITH EITHER <111> OR <100> ORIENTATIONS.

*
IN MANY SIMULATIONS, THERE IS AN INITIAL UNIFORM SUBSTRATE CONCENTRATION THAT IS USED ONLY TO PROVIDE JUNCTION DEPTH INFORMATION AND IS NOT OTHERWISE SIGNIFICANT. WHEN THIS IS THE CASE, MUCH COMPUTATION TIME AND PRINTED OUTPUT CAN BE SAVED BY SPECIFYING THE TYPE OF INITIAL SUBSTRATE IMPURITY AS EITHER P- OR N-TYPE, (+ OR -) AND NOT AS THE ACTUAL ELEMENT TYPE, B, P, SB OR AS. IF USED IN THIS WAY, THE IMPURITY CONCENTRATION SPECIFIED IS USED * ONLY IN THE CALCULATION OF OUTPUT INFORMATION SUCH AS THE JUNCTION DEPTHS, SHEET RESISTIVITIES, THRESHOLD VOLTAGES ETC. AND IS NOT ACTUALLY PROCESSED DURING HIGH TEMPERATURE PROCESSING STEPS. PLEASE NOTE THAT THIS CONCENTRATION REMAINS AT THE SAME UNIFORM LEVEL THROUGHOUT THE EXISTING SILICON, EVEN INTRINSIC EPI-LAYERS.

SUBSTRATE ORNT=<N> [,ELEM=<E> [,CONC=<N>]]

ORNT : THE CRYSTALLINE ORIENTATION OF THE WAFER. ONLY <111> OR <100> ORIENTATIONS ARE ALLOWED.

*
ELEM : THE TYPE OF IMPURITY INITIALLY IN THE SUBSTRATE WHOS UNIFORM CONCENTRATION IS SPECIFIED BY CONC. MAY BE ACTUAL IMPURITY DESIGNATION SUCH AS B, P, SB, OR AS, OR JUST THE IMPURITY TYPE SUCH AS + FOR P-TYPE OR - FOR N-TYPE.

CONC : THE UNIFORM IMPURITY CONCENTRATION OF THE ELEMENT SPECIFIED BY THE ELEM PARAMETER. DEFAULT VALUE = 0.0

* - THIS FEATURE CAN SUBSTANTIALLY REDUCE CPU TIME.

----- 8. INPUT/OUTPUT CARDS -----

THE INPUT/OUTPUT CARDS ARE THE PRINT, PLOT, SAVE AND LOAD CARDS. THE FIRST TWO OF THESE, THE PRINT AND PLOT CARDS, ARE USED FOR CONTROLLING THE HAROCOPY OUTPUT OF THE PROGRAM. THE VALUES ASSIGNED TO THE PARAMETERS OF THE PRINT AND PLOT CARDS DO NOT CHANGE UNTIL THEY ARE MODIFIED IN SUBSEQUENT PRINT OR PLOT CARDS. THE OTHER TWO INPUT/OUTPUT CARDS, THE SAVE AND LOAD, ARE USED TO SAVE THE CURRENT STATE OF THE PROCESS UNDER SIMULATION OR TO LOAD IN A PREVIOUSLY SAVED PROCESS AND RESUME PROCESSING FROM THE POINT AT WHICH IT WAS SAVED.

PRINT CARDS -----

THE PRINT CARDS CONTROL SUPREM'S PRINTED NUMERICAL OUTPUT, WHICH IS OF TWO BASIC TYPES. THE FIRST TYPE, CALLED THE HEADING INFORMATION, IS CONTROLLED BY THE PRINT CARD'S HEAD PARAMETER. THE HEADING CONTAINS INFORMATION ABOUT THE STEP CARD'S PARAMETERS AND OTHER STEP RELATED VARIABLES SUCH AS THE AMOUNT OF OXIDE OR SILICON GROWN OR ETCHED. THE HEADING ALSO LISTS THE AMOUNT OF OXIDE PRESENT, THE TOTAL SURFACE CONCENTRATION, JUNCTION DEPTHS, SHEET RESISTIVITIES, TOTAL AND INDIVIDUAL INTEGRATED IMPURITY CONCENTRATIONS AND, IF THE GATE MATERIAL IS SPECIFIED, THE THRESHOLD VOLTAGE. THE SECOND TYPE OF PRINTED NUMERICAL OUTPUT IS A LIST OF THE DEPTH AND CONCENTRATION AT EACH GRID POINT FOR BOTH THE TOTAL AND/OR INDIVIDUAL IMPURITY DISTRIBUTIONS. THESE ARE CONTROLLED BY THE PRINT CARD'S TOTL AND IDIV PARAMETERS.

THE PRINT CARD PARAMETERS ARE ALL LOGICAL FLAGS AND SO MUST BE SET TRUE OR FALSE BEFORE THE OUTPUT CAN BE GENERATED. SINCE THE OUTPUT ROUTINES ARE CALLED IMMEDIATELY AFTER THE COMPLETION OF A PROCESSING STEP, IF ANY OF THE PRINT OPTIONS ARE TO BE CHANGED FOR THAT STEP'S OUTPUT, THE PRINT CARD THAT MAKES THOSE CHANGES MUST APPEAR BEFORE THAT STEP CARD. PRINT CARD OPTIONS, ONCE SET, APPLY FOR ALL SUBSEQUENT STEPS UNTIL CHANGED BY LATER PRINT CARDS.

PRINT (HEAD=<L>) [,TOTL=<L>] [,IDIV=<L>]

HEAD : CONTROLS THE PRINTING OF THE HEADING INFORMATION. DEFAULT VALUE = FALSE.

TOTL : CONTROLS THE PRINTING OF THE NET IMPURITY CONCENTRATION VALUES VS. DEPTH AT EACH GRID POINT. DEFAULT VALUE = FALSE.

IDIV : CONTROLS THE PRINTING OF THE INDIVIDUAL IMPURITY CONCENTRATION VALUES VS. DEPTH AT EACH GRID POINT FOR EACH ELEMENT PRESENT. DEFAULT VALUE = FALSE.

PLOT CARD

PLOT CARDS CONTROL THE PLOTS OF IMPURITY CONCENTRATIONS VS. DEPTH. THEY MAY APPEAR AT ANY POINT IN A PROCESSING SEQUENCE AFTER THE INITIAL GRID AND SUBSTRATE CARDS. THE STANDARD PLOT OUTPUT FOR SUPREM IS DONE ON A LINE PRINTER. SOME SYSTEMS THAT HAVE LINE OR POINT PLOTTERS MAY OUTPUT THE PLOTS TO THEM INSTEAD OF THE LINE PRINTER, CHECK WITH THE PERSON RESPONSIBLE FOR MAINTENANCE OF SUPREM. ONLY FIVE OF THE PARAMETERS LISTED BELOW ARE USED WHEN PLOTTING ON THE LINE PRINTER. THE OTHER TWO, AXIS AND DATA, ARE DESCRIBED IN CASE YOUR SYSTEM USES A PLOTTER WITH SUPREM.

THE LINE PRINTER PLOTS ALL TAKE UP THE SAME AMOUNT OF SPACE ON A PAGE IN ORDER THAT DIFFERENT PLOTS CAN BE OVERLAYED. THIS MEANS IS THAT THE OXIDE IS PLOTTED IN A FIXED AMOUNT OF SPACE INDEPENDENT OF THE AMOUNT OF OXIDE. IF NO OXIDE EXISTS THE IS STILL ADJUSTED. THE SILICON IS ALSO PLOTTED IN THE SAME AMOUNT OF SPACE ON EACH PAGE, HOWEVER FOUR TIMES MORE AREA IS USED THAN FOR THE OXIDE. THE AMOUNT OF SILICON THAT IS PLOTTED, (I.E. THE PLOT WINDOW), IS SPECIFIED BY THE PLOT CARD'S WIND PARAMETER. THE MAXIMUM Y-AXIS VALUE HOWEVER MAY BE LARGER THAN THE WINDOW SINCE THE FOUR MINOR DIVISIONS OF THE SILICON AXIS ARE LIMITED TO WIDTHS FROM THE FOLLOWING SERIES: .01, .02, .025, .04, .05, .08, .1, .2, ETC. THE Y-AXIS REPRESENTS THE LOG OF THE CONCENTRATION AND ITS MINIMUM LOG VALUE IS SPECIFIED BY THE CMIN PARAMETER. THE NUMBER OF DECADES PLOTTED IS SPECIFIED BY THE NDEC PARAMETER.

THE OTHER FOUR PLOT CARD PARAMETERS ARE LOGICAL FLAGS WHICH DETERMINE WHAT INFORMATION IS TO BE PLOTTED. THE TOTL PARAMETER CONTROLS THE PLOTTING OF THE TOTAL OR NET CONCENTRATION AND THE IDIV PARAMETER CONTROLS THE PLOTTING OF THE INDIVIDUAL IMPURITY CONCENTRATIONS. THE AXIS PARAMETER CONTROLS THE PLOTTING OF THE AXIS, WHICH ALLOWS THE USER TO PLOT SEVERAL CURVES ON THE SAME SHEET WITHOUT REPLOTTING THE AXIS AT EACH STEP. (THIS IS NOT POSSIBLE ON MOST LINE PRINTERS SO THE AXIS PARAMETER IS IGNORED BY THE LINE PRINTER PLOT ROUTINE). THE DATA PARAMETER CONTROLS THE PRINT OF SOME STEP DATA AT THE BOTTOM OF THE PLOTS, SUCH AS THE OXIDE THICKNESS, THE STEP TIME AND TEMPERATURE. (AGAIN THIS DOES NOT APPLY TO LINE PRINTER PLOTS).

PLOT [WIND=<N>] [,CMIN=<N>] [,NDEC=<N>] [,TOTL=<L>] [,IDIV=<L>]
+ [AXIS=<L>] [,DATA=<L>]

WIND : AMOUNT OF SILICON PLOTTED IN MICRONS. DEFAULT VALUE = 4.

CMIN : LOG OF THE MINIMUM CONCENTRATION PLOTTED. DEFAULT VALUE = 14

NDEC : NUMBER OF DECADE OF CONCENTRATION PLOTTED. DEFAULT VALUE = 7

TOTL : CONTROLS THE PLOTTING OF THE NET IMPURITY CONCENTRATION VS. DEPTH. DEFAULT VALUE = FALSE.

IDIV : CONTROLS THE PLOTTING OF THE INDIVIDUAL IMPURITY CONCENTRATIONS VS. DEPTH FOR EACH ELEMENT PRESENT. DEFAULT VALUE = FALSE.

AXIS : CONTROLS THE PLOTTING OF AXIS. DEFAULT VALUE = FALSE.

DATA : CONTROLS THE PLOTTING OF STEP DATA BELOW THE PLOTTED CURVES. DEFAULT VALUE = FALSE.

SAVE AND LOAD CARDS

THE SAVE AND LOAD CARDS ARE USED TO STORE AND READ THE INFORMATION NECESSARY TO RESTART A PROCESSING SEQUENCE. THEIR MAIN USE IS FOR SIMULATION RUN SPLITS, IN WHICH FOR EXAMPLE, SEVERAL EMITTER DIFFUSION TIMES MAY BE SIMULATED WITHOUT RERUNNING THE ENTIRE PROCESS FOR EACH DIFFUSION TIME. THE SAVE CARDS MAY APPEAR AT ANY POINT IN THE PROCESSING SEQUENCE AFTER THE INITIAL TITLE, GRID AND SUBSTRATE CARDS. THE LOAD CARD SHOULD APPEAR IMMEDIATELY AFTER THE INITIAL TITLE, GRID AND SUBSTRATE CARDS.

THE SAVE AND LOAD CARDS HAVE ONLY TWO PARAMETERS. ONE SPECIFIES THE FORTRAN LOGICAL UNIT NUMBER THAT IS ASSIGNED TO THE DATA FILE IN THE JOB CONTROL LANGUAGE DECK WHILE THE OTHER SPECIFIES THE TYPE OF DATA TRANSFER.

SAVE LUNM=<N> , TYPE=<FT>

LOAD LUNM=<N> , TYPE=<FT>

LUNM : A FORTRAN I/O LOGICAL UNIT NUMBER WHICH HAS BEEN ASSIGNED TO A DATA FILE IN THE J.C.L DECK.

TYPE : DESCRIBES THE TYPE OF DATA TRANSFER AS EITHER ASCII OR BINARY TYPE. INFORMATION TRANSFER IN BINARY FORM IS ABOUT TWENTY FASTER THAN ASCII AND THE DISC STORAGE IS MUCH LESS.

C. PROCESS/MODEL CARDS

STEP CARD

STEP CARDS ARE USED TO SPECIFY THE PROCESSING STEP TYPES AND PARAMETERS. THERE ARE CURRENTLY SIX DIFFERENT TYPES OF PROCESSING STEPS THAT CAN BE MODELED BY SUPREMO; ION IMPLANTATION, PREDEPOSITION, OXIDATION, EPITAXIAL GROWTH, LOW TEMPERATURE OXIDE DEPOSITION AND ETCHING. DRIVE-INS ARE MODELED BY OXIDATIONS IN NITROGEN OR NEUTRAL AMBIENTS. EACH STEP IN A PROCESSING SEQUENCE USES THE IMPURITY DISTRIBUTIONS THAT RESULTED FROM THE PREVIOUS STEP AS THE STARTING POINT FOR ITS CALCULATIONS.

EACH TYPE OF STEP HAS ITS OWN PARAMETER LIST, THOUGH THEY MAY USE MANY OF THE SAME PARAMETERS. THE VALUE OF ANY STEP PARAMETER THAT IS NOT SPECIFIED IS SET TO ZERO, WITH THE EXCEPTION OF TEMPERATURE, WHICH WILL USE THE LAST SPECIFIED TEMPERATURE. FOLLOWING IS A DESCRIPTION OF EACH STEP TYPE AND ITS ASSOCIATED PARAMETER LIST.

ION IMPLANTATION

ION IMPLANT STEPS MAY BE SPECIFIED IN TWO WAYS:

(1) IF THE IMPLANT ENERGY IS SPECIFIED THEN THE PROGRAM USES INTERNALLY STORED INFORMATION TO CALCULATE THE PROFILE. IN THIS CASE THE PROFILE IS A TWO-SIDED GAUSSIAN FOR THE ELEMENTS, ARSENIC, PHOSPHORUS AND ANTIMONY, AND A MODIFIED PEARSON TYPE-IV DISTRIBUTION FOR BORON.

(2) IF THE RANGE AND STANDARD DEVIATION ARE SPECIFIED THEN SUPREM USES THESE VALUES TO CALCULATE A SIMPLE GAUSSIAN DISTRIBUTION FOR THE ELEMENT.

STEP TYPE=IMPL, ELEM=<E>, DOSE=<N>, (AKEV=<N>) OR (RANG=<N>, STDV=<N>)
+ [,MODL=<M>]

ELEM : THE IMPURITY ELEMENT TO BE IMPLANTED (B, P, SB, AS).

DOSE : THE IMPLANT DOSE IN ATOMS/SQUARE CENTIMETER.

AKEV : THE IMPLANT ENERGY IN KEV.

RANG : THE RANGE OF THE SIMPLE GAUSSIAN DISTRIBUTION IN MICRONS.

STDV : THE STANDARD DEVIATION OF THE SIMPLE GAUSSIAN DISTRIBUTION IN MICRONS.

MODL : THE NAME OF AN ELEMENT OR SPECIAL PURPOSE MODEL.

ETCH STEP

ETCHES IN SUPREM CAN BE EITHER HIGH OR LOW TEMPERATURE. A LOW TEMPERATURE ETCH IS ONE IN WHICH THE TEMPERATURE IS BELOW 200 DEGREES CENTIGRADE. IN LOW TEMPERATURE ETCHES THE AMOUNT OF OXIDE ETCHED AWAY IS EQUAL TO THE ETCH RATE TIMES THE STEP TIME. ANY LOW TEMPERATURE ETCH STOPS WHEN THE ALL OF THE OXIDE HAS BEEN REMOVED. IF EITHER THE TIME OR ETCH RATE PARAMETER IS ZERO OR NOT SPECIFIED THEN ALL OF THE OXIDE IS REMOVED.

IN HIGH TEMPERATURE ETCHES, THE OXIDE IS ASSUMED TO BE ETCHED AWAY IN A NEGLIGABLE AMOUNT OF TIME, AND SO THE AMOUNT OF SILICON REMOVED IS EQUAL TO THE STEP TIME TIMES THE ETCH RATE. IN THE CURRENT VERSION OF SUPREM THE IMPURITIES IN THE REMAINING MATERIAL IS NOT REDISTRIBUTED, I.E. IS ASSUMED TO BE NEGLIGABLE.

STEP TYPE=ETCH, TEMP=<N> [,TIME=<N>, ERTE=<N>] [,MODL=<M>]

TEMP : THE SILICON TEMPERATURE DURING THE STEP IN DEGREES CENTIGRADE.

TIME : THE TOTAL STEP TIME IN MINUTES.

ERTE : THE ETCH RATE IN MICRONS/MINUTE.

MODL : THE NAME OF AN ELEMENT OR SPECIAL PURPOSE MODEL.

LOW TEMPERATURE OXIDE DEPOSITION STEP

IN THIS STEP, DOPED OR UNDOPED OXIDE IS DEPOSITED ON THE SILICON SURFACE OR ON TOP OF ANY EXISTING OXIDE. THE AMOUNT OF OXIDE DEPOSITED IS EQUAL TO THE STEP TIME TIMES THE GROWTH RATE. IF THE DEPOSITED OXIDE IS TO BE DOPED THEN THE IMPURITY IS SPECIFIED BY THE ELEM PARAMETER WHILE CONC SPECIFIES IT'S UNIFORM IMPURITY CONCENTRATION.

STEP TYPE=DEPO, TIME=<N>, GRTE=<N> [,ELEM=<E>, CONC=<N>] [,MODL=<M>]

TIME : THE TOTAL STEP TIME IN MINUTES.

GRTE : THE OXIDE GROWTH RATE IN MICRONS/MINUTE.

ELEM : THE OXIDE DOPING IMPURITY (B, P, SB, AS).

CONC : THE IMPURITY CONCENTRATION IN THE DEPOSITED OXIDE LAYER IN ATOMS/CUBIC CENTIMETER.

MODL : THE NAME OF AN ELEMENT OR SPECIAL PURPOSE MODEL.

OXIDATION STEP (AND DRIVE-IN)

THE OXIDATION STEP IS A HIGH TEMPERATURE STEP WHICH INCLUDES THE REDISTRIBUTION OF THE IMPURITIES PRESENT DUE TO DIFFUSION AND EVAPORATION. IN ADDITION IF THE AMBIENT INDICATED BY THE OXIDATION MODEL SPECIFIED BY THE MODL PARAMETER IS NOT A NEUTRAL ONE, THEN IMPURITY REDISTRIBUTION DUE TO THE GROWTH OF OXIDE ALSO OCCURS. THE TEMP PARAMETER SPECIFIES THE WAFER TEMPERATURE AT THE BEGINNING OF THE STEP. THE FINAL TEMPERATURE IS EQUAL TO THE SPECIFIED INITIAL TEMPERATURE PLUS, THE TEMPERATURE RATE OF CHANGE SPECIFIED BY TRTE, TIMES THE TOTAL STEP TIME. THE OXIDATION AMBIENT IS SPECIFIED BY AN OXIDATION MODEL CARD REFERENCE (SEE OXIDATION MODELS). OTHER MODEL CARDS MAY ALSO BE REFERENCED IN THE SAME CARD BUT ONLY ONE OXIDATION MODEL REFERENCED IS ALLOWED. IF NO OXIDATION MODEL IS REFERENCED, THEN A NIT0 MODEL IS ASSUMED.

STEP TYPE=OXID, TIME=<N> [,TEMP=<N>] [,TRTE=<N>] [,MODL=<M>]

TIME : THE TOTAL STEP TIME IN MINUTES.

TEMP : THE WAFER TEMPERATURE AT THE START OF THE STEP IN DEGREES CENTIGRADE. DEFAULT VALUE = LAST SPECIFIED STEP TEMPERATURE.

TRTE : THE TEMPERATURE RATE OF CHANGE IN DEGREES/MINUTE. DEFAULT VALUE = 0.

MODL : THE NAME OF AN OXIDATION, ELEMENT OR SPECIAL PURPOSE MODEL.

PREDEPOSITION STEP (NON-IMPLANT)

THE PREDEPOSITION STEP MODELS THE INTRODUCTION OF AN IMPURITY ELEMENT FROM A CONSTANT SOURCE AT THE SILICON SURFACE. SUPREM DOES NOT CARE ABOUT DETAILS OF THE IMPURITY SOURCE. THE CONC PARAMETER SPECIFIES THE SOURCE CONCENTRATION AT THE SURFACE AND THE SOURCE ELEMENT TYPE IS INDICATED BY THE ELEM PARAMETER. THE SILICON TEMPERATURE AT THE START OF THE STEP IS SPECIFIED BY THE TEMP PARAMETER WHILE THE FINAL TEMPERATURE IS EQUAL TO THE INITIAL TEMPERATURE, PLUS THE TEMPERATURE-RATE-OF-CHANGE, SPECIFIED BY TRTE, TIMES THE TOTAL STEP TIME.

STEP TYPE=POEP, ELEM=<E>, CONC=<N> TIME=<N> [,TEMP=<N>] [,TRTE=<N>]
+ [,MODL=<M>]

ELEM : THE IMPURITY ELEMENT BEING INTRODUCED (B, P, SB, AS).

CONC : THE SURFACE GAS CONCENTRATION OF THE IMPURITY SPECIFIED BY ELEM IN ATOMS/CUBIC CENTIMETER.

TIME : THE TOTAL STEP TIME IN MINUTES.

TEMP : THE WAFER TEMPERATURE AT THE BEGINNING OF THE STEP IN DEGREES CENTIGRADE. DEFAULT VALUE = LAST SPECIFIED STEP TEMPERATURE.

TRTE : THE TEMPERATURE RATE OF CHANGE IN DEGREES CENTIGRADE/MINUTE. DEFAULT VALUE = 0.

MODL : THE NAME OF AN ELEMENT OR SPECIAL PURPOSE MODEL.

EPITAXIAL GROWTH STEP

THIS STEP MODELS THE EPITAXIAL GROWTH OF A SILICON LAYER AT HIGH TEMPERATURES, ON TOP OF AN INITIAL LAYER OF SILICON. THE ADDED SILICON MAY DOPED OR INTRINSIC, IF IT IS TO BE DOPED, THE IMPURITY ELEMENT IS SPECIFIED BY THE ELEM PARAMETER AND THE BULK GAS CONCENTRATION (NOT THE SURFACE) IS SPECIFIED BY THE CONC PARAMETER. THE AMOUNT OF SILICON GROWN IS EQUAL TO THE GROWTH RATE, SPECIFIED BY GRTE, TIMES THE TOTAL STEP TIME. THE WAFER TEMPERATURE AT THE BEGINNING OF THE STEP IS SPECIFIED BY THE TEMP PARAMETER. THE FINAL TEMPERATURE IS THE INITIAL TEMPERATURE PLUS, THE TEMPERATURE-RATE-OF-CHANGE SPECIFIED BY TRTE, TIMES THE TOTAL STEP TIME. THE MODL PARAMETER MAY BE USED TO SPECIFY ANY DESIRED ELEMENT, EPITAXY OR SPECIAL PURPOSE MODELS.

STEP TYPE=EPIT, TIME=<N>, GRTE=<N> [,TEMP=<N>] [,TRTE=<N>] [,MODL=<M>]
* [ELEM=<E>, CONC=<N>]

TIME : THE TOTAL STEP TIME IN MINUTES.

GRTE : THE GROWTH RATE OF THE EPI-LAYER IN MICRONS/MINUTE.

TEMP : THE WAFER TEMPERATURE AT THE BEGINNING OF THE STEP IN DEGREES CENTIGRADE. DEFAULT VALUE = LAST SPECIFIED STEP TEMPERATURE.

TRTE : THE TEMPERATURE RATE OF CHANGE IN DEGREES/MINUTE. DEFAULT VALUE = 0.

MODL : THE NAME OF A ELEMENT, EPITAXY OR SPECIAL PURPOSE MODELS, TION MODEL.

ELEM : THE IMPURITY ELEMENT IN THE GROWN SILICON (B, P, SB, AS).

CONC : THE BULK GAS PHASE CONCENTRATION OF THE IMPURITY SPECIFIED BY ELEM IN ATOMS/CUBIC CENTIMETER.

 MODEL CARD

THE MODEL CARDS ALLOW THE USER TO MODIFY INTERNAL PROGRAM COEFFICIENTS. THERE ARE FOUR MAIN TYPES OF MODEL CARDS AND TWO OF THESE, ELEMENT AND OXIDATION, ARE DIVIDED INTO FOUR SUBTYPES. EACH OF THESE TYPES OR SUBTYPES ARE IDENTIFIED BY A UNIQUE THREE CHARACTER NAME. IN ADDITION THERE ARE FIVE OF EACH OF THE MODEL TYPES OR SUBTYPES, IDENTIFIED BY A SINGLE DIGIT NUMBER FOLLOWING THE THREE CHARACTER IDENTIFIER. THE MODEL TYPES, SUBTYPES AND THEIR NAMES ARE LISTED BELOW.

TYPE	SUBTYPE	NAME (<M>)	
ELEMENT MODELS	(BORON)	MBO#	# = 1 - 5
	(PHOSPHORUS)	MPH#	# = 1 - 5
	(ANTIMONY)	MSB#	# = 1 - 5
	(ARSENIC)	MAS#	# = 1 - 5
OXIDATION MODELS	(STEAM)	STM#	# = 1 - 5
	(WET)	WET#	# = 1 - 5
	(DRY)	DRY#	# = 1 - 5
	(NITROGEN)	NIT#	# = 1 - 5
EPITAXY MODELS	---	EPI#	# = 1 - 5
SPECIAL PURPOSE MODELS	---	SPM#	# = 1 - 5

A PARTICULAR MODEL IS REFERENCED IN A STEP CARD BY ASSIGNING THE MODEL NAME TO A MODL PARAMETER (I.E. MODL=MAS2). THIS RESULTS IN THE PARAMETER VALUES SPECIFIED ON THE MODEL CARD OF THAT NAME BEING ASSIGNED TO THE CORRESPONDING PROGRAM VARIABLES. THESE NEW PARAMETER VALUES WILL BE USED IN ALL SUBSEQUENT STEPS UNLESS REASSIGNED BY ANOTHER REFERENCE TO A MODEL CARD OF THE SAME TYPE OR SUBTYPE. IF A STEP REFERENCES A MODEL WITH THE NUMBER ZERO AS THE IDENTIFYING DIGIT, THEN ALL OF THE PROGRAM VARIABLES ASSOCIATED WITH MODELS OF THAT TYPE OR SUBTYPE ARE RESET TO THEIR DEFAULT VALUES.

FOLLOWING IS A DESCRIPTION OF EACH OF THE MODEL TYPES AND THEIR PARAMETER LISTS:

ELEMENT MODELS

THE ELEMENT MODELS ALLOW THE USER TO CHANGE THOSE PARAMETERS WHICH ARE ELEMENT SPECIFIC. THERE ARE FOUR ELEMENT MODEL SUBTYPES CORRESPONDING TO EACH OF THE ALLOWABLE IMPURITY ELEMENTS; BORON, PHOSPHORUS, ANTIMONY AND ARSENIC. THE ELEMENT THAT THE MODEL CARD'S PARAMETERS APPLY TO IS SPECIFIED BY THE NAME PARAMETER ASSIGNMENT, THE ELEMENT AND THE CORRESPONDING MODEL NAMES ARE:

BORON	:	MB01, MB02, MB03, MB04, MB05
PHOSPHORUS	:	MPH1, MPH2, MPH3, MPH4, MPH5
ANTIMONY	:	MSB1, MSB2, MSB3, MSB4, MSB5
ARSENIC	:	MAS1, MAS2, MAS3, MAS4, MAS5

THE COEFFICIENTS THAT CAN BE ACCESSED THROUGH THE ELEMENT MODEL CARDS ARE LISTED BELOW, ALONG WITH THE WAY THE MODEL CARD'S PARAMETERS ARE USED TO CALCULATE THEM.

OXIDE DIFFUSION COEFFICIENT $= DOX0 * EXP(-EOX0/KT)$

SEGREGATION COEFFICIENT $= SEG0 * EXP(-SEGE/KT)$

SURFACE TRANSPORT COEFFICIENT $= STC0 * EXP(-STCE/KT)$

MOVING BOUNDARY FLUX TERM $= HSF0 * EXP(-HSFE/KT)$

SILICON DIFFUSION COEFFICIENT *

(NON-OXIDIZING) $= DSXN * EXP(-ESXN/KT)$

(FOR BORON IN DRY OXYGEN) $= DSXN * EXP(-ESXN/KT) + DSXD * EXP(-ESXD/KT)$

(FOR BORON IN WET OXYGEN) $= DSXN * EXP(-ESXN/KT) + DSXW * EXP(-ESXW/KT)$

(ALL OTHERS IN DRY OXYGEN) $= DSXD * EXP(-ESXD/KT)$

(ALL OTHERS IN WET OXYGEN) $= DSXW * EXP(-ESXW/KT)$

WHERE KT = BOLTZMAN'S CONSTANT * THE TEMPERATURE IN KELVIN DEGREES.

THE PARAMETER BETA IS USED TO MODIFY THE SILICON DIFFUSION COEFFICIENT OF IMPURITIES BY A MULTIPLICATIVE FACTOR CALCULATED BY.

FACTOR = $(1 + BETA * (N \text{ OR } P) / NIEF) / (1 + BETA)$

WHERE (N OR P) IS THE FREE CARRIER CONCENTRATION AT A GRID POINT AT THE PROCESS TEMPERATURE, AND NIEF IS THE INTRINSIC CARRIER CONCENTRATION AT THE PROCESS TEMPERATURE.

IF THE IMPURITY CONCENTRATION IS LESS THAN 10% OF NIEF THEN THE NUMBER CARRIERS EQUALS NIEF AND THUS FACTOR = 1.

THE CLUSTERING OF ARSENIC AT HIGH CONCENTRATION LEVELS IS CONTROLLED BY THE FOLLOWING THREE PARAMETERS.

(EQUILIBRIUM CLUSTERING COEFFICIENT) = $KEQ0 \cdot \exp(-KEQE/KT)$
 (DECLUSTERING COEFFICIENT) = $KDC0 \cdot \exp(-KDCE/KT)$
 (NUMBER OF ATOMS PER CLUSTER) = CLST

MODEL NAME=<M> [,DOX0=<N>] [,EOX0=<N>] [,DSXN=<N>] [,ESXN=<N>]
 + [,DSXD=<N>] [,ESXD=<N>] [,DSXH=<N>] [,ESXH=<N>]
 + [,SEG0=<N>] [,SEGE=<N>] [,HSF0=<N>] [,HSFE=<N>]
 + [,STC0=<N>] [,STCE=<N>] [,BETA=<N>] [,CLST=<N>]
 + [,KEQ0=<N>] [,KEQE=<N>] [,KDC0=<N>] [,KDCE=<N>]

DOX0 : PRE-EXPONENTIAL TERM OF THE SILICON DIOXIDE DIFFUSION COEFFICIENT IN MICRONS SQUARED/MINUTE.

EOX0 : ACTIVATION ENERGY OF THE SILICON DIOXIDE DIFFUSION COEFFICIENT IN ELECTRON VOLTS.

DSXN : PRE-EXPONENTIAL TERM OF THE INTRINSIC SILICON DIFFUSION COEFFICIENT IN MICRONS SQUARED/MINUTE.

DSXN : ACTIVATION ENERGY OF INTRINSIC SILICON DIFFUSION COEFFICIENT IN ELECTRON VOLTS.

DSXD : PRE-EXPONENTIAL TERM OF THE SILICON DIFFUSION DRY OXIDATION ENHANCEMENT COEFFICIENT IN MICRONS SQUARED/MINUTE.

ESXD : ACTIVATION ENERGY OF THE SILICON DIFFUSION DRY OXIDATION ENHANCEMENT COEFFICIENT IN ELECTRON VOLTS.

SEG0 : PRE-EXPONENTIAL TERM OF THE SEGREGATION COEFFICIENT. DEFINED THE CONCENTRATION IN THE SILICON OVER THE CONCENTRATION IN THE OXIDE.

SEGE : THE ACTIVATION ENERGY OF THE SEGREGATION COEFFICIENT IN ELECTRON VOLTS.

STC0 : THE PRE-EXPONENTIAL CONSTANT OF THE SURFACE TRANSPORT COEFFICIENT IN MICRONS/MINUTE.

STCE : THE ACTIVATION ENERGY OF THE SURFACE TRANSPORT COEFFICIENT IN ELECTRON VOLTS.

HSF0 : PRE-EXPONENTIAL CONSTANT OF THE MOVING BOUNDARY FLUX IN MICRONS/MINUTE.

HSFE : PRE-EXPONENTIAL CONSTANT OF THE MOVING BOUNDARY FLUX IN ELECTRON VOLTS.

BETA : COEFFICIENT RELATING THE EFFECT OF UNCHARGED VACANCIES ON THE DIFFUSION COEFFICIENT.

CLST : NUMBER OF IMPURITYS ATOMS PER CLUSTER.

KEQ0 : PRE-EXPONENTIAL CONSTANT OF THE EQUILIBRIUM CLUSTERING COEFFICIENT.

KEQE : ACTIVATION ENERGY OF THE EQUILIBRIUM CLUSTERING COEFFICIENT.

KDC0 : PRE-EXPONENTIAL CONSTANT OF THE DECLUSTERING COEFFICIENT.

KDCE : ACTIVATION ENERGY OF THE DECLUSTERING COEFFICIENT.

OXIDATION MODELS

THE OXIDATION MODELS HAVE TWO FUNCTIONS; 1) TO SPECIFY THE TYPE OF AMBIENT THAT THE STEP IS BEING CARRIED OUT IN, AND, 2) TO MODIFY THE OXIDE GROWTH RATE PARAMETERS FOR THAT AMBIENT. THE OXIDATION MODEL NAMES ALLOW DISTINCTION BETWEEN FOUR AMBIENTS, THE AMBIENT TYPES AND THE CORRESPONDING MODEL NAMES ARE LISTED BELOW.

STEAM : STM1, STM2, STM3, STM4, STM5
WET O2 : WET1, WET2, WET3, WET4, WET5
DRY O2 : DRY1, DRY2, DRY3, DRY4, DRY5
NITROGEN : DRY1, DRY2, DRY3, DRY4, DRY5

THE COEFFICIENTS THAT ARE CAN MODIFIED BY THE OXIDATION MODEL PARAMETERS ARE THE LINEAR AND PARABOLIC OXIDE GROWTH RATES. THE EXPRESSIONS FOR THESE COEFFICIENTS USING THE OXIDATION MODEL PARAMETERS ARE:

LINEAR GROWTH RATE $\square LRTE \star EXP(-LREA/KT) \star PRES$

PARABOLIC GROWTH RATE $\square PRTE \star EXP(-PREA/KT) \star PRES$

WHERE KT = BOLTZMANS CONSTANT * TOME TEMPERATURE IN KELVIN DEGREES.

MODEL NAME=<M> [,LRTE=<N>] [,LREA=<N>] [,PRTE=<N>] [,PREA=<N>]
+ [,PRES=<N>]

LRTE : PRE-EXPONENTIAL TERM FOR CALCULATING THE LINEAR GROWTH RATE IN MICRONS/MINUTE.

LREA : ACTIVATION ENERGY FOR CALCULATING THE LINEAR GROWTH RATE IN ELECTRON VOLTS.

PRTE : PRE-EXPONENTIAL TERM FOR CALCULATING THE PARABOLIC GROWTH RATE IN MICRONS SQUARED/MINUTE.

PREA : ACTIVATION ENERGY FOR CALCULATING THE PARABOLIC GROWTH RATE IN ELECTRON VOLTS.

PRES : THE AMBIENT PRESSURE IN ATMOSPHERES.

EPITAXY MODELS

THE EPITAXY MODELS ARE USED TO MODIFY THE IMPURITY FLUX PARAMETERS USED BY THE EPITAXIAL GROWTH ROUTINE. THERE ARE FIVE EPI MODELS, NUMBERED ONE THROUGH FIVE: EPI1, EPI2, EPI3, EPI4, AND EPI5. THE PARAMETER LIST OF THE EPI MODELS IS DESCRIBED BELOW.

MODEL NAME=<M> [,FRAC=<N>] [,FAUT=<N>]

FRAC : A MULTIPLIER OF THE EVAPORATION COEFFICIENT FOR AUTODOPING,

FAUT : THE FRACTION OF DOPANT RELEASED FROM THE INTERFACE THAT IS REABSORBED.

SPECIAL PURPOSE MODELS

THE SPECIAL PURPOSE MODELS ARE SO CALLED BECAUSE THEIR PARAMETERS ARE ONES THAT DON'T FIT IN WITH ANY OF THE OTHER MODELS, AND IN SOME CASES ARE NOT STRICTLY MODEL PARAMETERS IN THE SAME SENSE AS THE OTHERS. THERE ARE FIVE SUCH SPECIAL PURPOSE MODELS, NUMBERED ONE THROUGH FIVE, THEIR PARAMETER LIST IS DESCRIBED BELOW.

SPECIAL PURPOSE MODELS : SPM1, SPM2, SPM3, SPM4, SPM5

MODEL NAME=<M> [,NIEF=<N>] [,NIEA=<N>] [,GATE=<G>] [,QSSQ=<N>]
+ [,CBLK=<N>]

NIEF : THE PRE-EXPONENTIAL CONSTANT USED TO CALCULATE THE EFFECTIVE INTRINSIC CARRIER CONCENTRATION, NI, AS A FUNCTION OF TEMPERATURE. (I.E. $NI = NIEF * \exp(-NIEA/KT) * (T ** 1.5)$ WHERE K IS BOLTZMAN'S CONSTANT AND T IS IN KELVIN DEGREES). DEFAULT VALUE = 2.09717E16 ATOMS/CUBIC CENTIMETER.

NIEA : THE ACTIVATION ENERGY USED IN THE ABOVE EXPRESSION FOR CALCULATING THE EFFECTIVE INTRINSIC CARRIER CONCENTRATION. DEFAULT VALUE = 0.561839 EV.

GATE : THE GATE MATERIAL USED TO CALCULATE THE THRESHOLD VOLTAGE. THERE ARE THREE TYPES THAT MAY BE SPECIFIED, ALUMINUM, P+, AND N+. THEIR SYMBOLS (<G>) ARE RESPECTIVELY, AL, +, AND -.

QSSQ : THE NUMBER OF SURFACE STATES AT THE SILICON/OXIDE INTERFACE IN STATES/SQUARE CENTIMETER USED FOR CALCULATING THE THRESHOLD VOLTAGES. DEFAULT VALUE = 0.

CBLK : INDICATES THE TYPE BULK CONTACT.

CBLK = 0.	FOR CONTACT AT THE SUBSTRATE (LAST SI POINT)
CBLK = 1.	FOR CONTACT AT THE SURFACE (FIRST SI POINT)
CBLK = <N>	ARBITRARY CONCENTRATION AT BULK CONTACT. POSITIVE FOR P-TYPE, NEGATIVE FOR N-TYPE.

DEFAULT PARAMETER VALUES

BELOW ARE THE DEFAULT VALUES OF THE VARIOUS MODEL PARAMETERS USED IN SUPREM. THOSE PARAMETERS THAT ARE ORIENTATION DEPENDENT AND WHOSE <100> VALUE IS NOT KNOWN USE THE <111> VALUE AS THE DEFAULT.

NAME	ORNT.	I	BORON	I	PHOSPHORUS	I	ANTIMONY	I	ARSENIC	I
SEGREGATION COEFFICIENT:										
SEGO	<111>	I	1126.0	I	10.0	I	10.0	I	10.0	I
SEGO	<100>	I	2208.0	I	10.0	I	10.0	I	10.0	I
SFGE	<111>	I	0.91	I	0.0	I	0.0	I	0.0	I
SEGE	<100>	I	0.96	I	0.0	I	0.0	I	0.0	I
SURFACE TRANSPORT COEFFICIENT:										
STCO		I	1.674E7	I	9.0E5	I	1.5E3	I	9.0E5	I
STCE		I	2.481	I	1.99	I	1.04	I	1.99	I
MOVING BOUNDARY FLUX TERM:										
MSFO		I	0.1	I	0.1	I	0.1	I	0.1	I
MSFE		I	0.0	I	0.0	I	0.0	I	0.0	I
SILICON DIOXIDE DIFFUSION COEFFICIENT:										
DOXD		I	1.896E6	I	4.56E7	I	7.86E25	I	1.05E10	I
EOXD		I	3.53	I	3.5	I	8.75	I	4.89	I
SILICON DIFFUSION COEFFICIENT (NEUTRAL OR NON-OXIDIZING AMBIENT):										
DSXN	<111>	I	3.3324E9	I	2.31E10	I	7.74E10	I	1.440E11	I
DSXN	<100>	I	3.3324E9	I	2.31E10	I	7.74E10	I	1.440E11	I
ESXN	<111>	I	3.42565	I	3.66	I	3.98	I	4.08	I
ESXN	<100>	I	3.42565	I	3.66	I	3.98	I	4.08	I
SILICON DIFFUSION COEFFICIENT (DRY O2 OXIDIZING AMBIENT):										
DSXD	<111>	I	1.608E1	I	2.31E10	I	7.74E10	I	1.440E11	I
DSXD	<100>	I	5.502E2	I	4.158E10	I	7.74E10	I	1.440E11	I
ESXD	<111>	I	1.4530	I	3.66	I	3.98	I	4.08	I
ESXD	<100>	I	1.69065	I	3.66	I	3.98	I	4.08	I
SILICON DIFFUSION COEFFICIENT (WET O2 OXIDIZING AMBIENT):										
DSXW	<111>	I	1.608E1	I	2.31E10	I	7.74E10	I	1.440E11	I
DSXW	<100>	I	5.502E2	I	4.158E10	I	7.74E10	I	1.440E11	I
ESXW	<111>	I	1.430	I	3.66	I	3.98	I	4.08	I
ESXW	<100>	I	1.690	I	3.66	I	3.98	I	4.08	I
BETA:										
BETA		I	3.0	I	1.0	I	1.0	I	100.0	I
CLUSTERING SIZE:										
CLST		I	0.0	I	0.0	I	0.0	I	4.0	I
EQUILIBRIUM CLUSTERING COEFFICIENT:										
KEQ0		I	0.0	I	0.0	I	0.0	I	2.72E-17	I
KEQE		I	0.0	I	0.0	I	0.0	I	-0.305	I

NAME	ORNT.	I	BORON	I	PHOSPHORUS	I	ANTIMONY	I	ARSENIC	I
DECLUSTERING RATE:										
KDC0		I	0.0		I	0.0		I	0.0	
KDCE		I	0.0		I	0.0		I	4.8E8	
									2.6	

NAME	ORNT	STEAM	I	WET	I	DRY	I	NEUTRAL	I
LINEAR OXIDE GROWTH RATE:									
LRTE	<111>	I	2.717E6		I	1.038E5		I	0.0
LRTE	<100>	I	1.617E6		I	6.181E4		I	0.0
LREA	<111>	I	2.05		I	2.00		I	0.0
LREA	<100>	I	2.05		I	2.00		I	0.0

PARABOLIC OXIDE GROWTH RATE:									
PRTE	<111>	I	6.43		I	12.87		I	0.0
PRTE	<100>	I	6.43		I	12.87		I	0.0
PREA	<111>	I	0.78		I	1.23		I	0.0
PREA	<100>	I	0.78		I	1.23		I	0.0

REFERENCES FOR DEFAULT PARAMETER VALUES

SEGREGATION COEFFICIENTS:

BORON:

D. A. ANTONIADIS, A. G. GONZALEZ AND R. W. DUTTON, J. ELECTROCHEM. SOC., (125), P. 813, (1978).

ALL OTHER IMPURITIES:

H. F. WOLF, SEMICONDUCTORS, INTERSCIENCE, 1971, P. 361.

SURFACE TRANSPORT COEFFICIENTS:

P. H. LANGER AND J. T. GOLDSTEIN, J. ELECTROCHEM SOC., APR. 1974.

MOVING BOUNDARY FLUX TERM:

SEE PAGE 21 OF THIS TECHNICAL REPORT.

SILICON DIOXIDE DIFFUSION COEFFICIENT:

M. GHEZZO AND D. M. BROWN, J. ELECTROCHEM SOC., JAN. 1973.

SILICON DIFFUSION COEFFICIENT (NEUTRAL OR NON-OXIDIZING AMBIENT):

BORON:

D. A. ANTONIADIS, A. G. GONZALEZ AND R. W. DUTTON, J. ELECTROCHEM SOC., (125), P. 813, (1978).

PHOSPHORUS:

R. B. FAIR AND J. C. C. TSAI, J. ELECTROCHEM SOC., (124), P. 1107, (1977).

ANTIMONY:

H. F. WOLF, SEMICONDUCTORS, INTERSCIENCE, 1971, PP. 153 & 363.

ARSENIC:

T. L. CHIU AND H. N. GOSH, IBM J. RES. DEV., 15, 472, (1971).

SILICON DIFFUSION COEFFICIENT (DRY O₂ OXIDIZING AMBIENT):

BORON:

SAME REFERENCE AS FOR NEUTRAL AMBIENT ABOVE.

PHOSPHORUS:

R. B. FAIR, PRIVATE COMMUNICATION.

ANTIMONY:

DIFFUSIVITY SAME AS FOR NEUTRAL AMBIENT.

ARSENIC:

DIFFUSIVITY SAME AS FOR NEUTRAL AMBIENT.

SILICON DIFFUSION COEFFICIENT (WET O₂ OXIDIZING AMBIENT):

DIFFUSIVITY SAME AS FOR DRY O₂ AMBIENT FOR ALL ELEMENTS.

BETA:

SEE PAGE 13 OF THIS TECHNICAL REPORT.

ALL ARSENIC CLUSTERING INFORMATION

F. F. MOREHEAD, PRIVATE COMMUNICATION.

LINEAR OXIDE GROWTH RATE COEFFICIENT:

R. E. DEAL, J. ELECTROCHEM SOC., (125), P. 578, (1978).

PARABOLIC OXIDE GROWTH RATE COEFFICIENT:

SAME REFERENCE AS FOR LINEAR GROWTH RATE ABOVE.

APPENDIX 2

Following are two examples of processes simulated by SUPREM II. The first example is a CMOS process where the p-well fabrication is simulated and the final n-channel threshold voltage is calculated, first without and then with a threshold voltage tailoring phosphorus implant. The second example is a bipolar process including an arsenic buried collector, a boron base and a phosphorus emitter. This process is a variant of a Stanford University standard process.

Both of the following two examples were designed so that the use of the SUPREM II simulator could be illustrated under a wide variety of processes. It is not implied that any of these processes would result into useful electronic devices.

*** STANFORD UNIVERSITY PROCESS ENGINEERING MODELS PROGRAM ***

*** VERSION 0-02 ***

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1....TITL  CMOS P-WELL SIMULATION
2....GRID  DYSI=0.01, DPTH=0.6, YMAX=2.5
3....SUBS  ORNT=100, ELEM=, CONC=1E15

4....COMM  STARTING OXIDE THICKNESS OF 500 A.
5....STEP  TYPE=DEPO, TIME=1, GRTE=0.050

6....PLOT  TOTL=Y, CMIN=14, NDEC=4, WIND=1.8

7....COMM  P-WELL IMPLANT
8....STEP  TYPE=IMPL, ELEM=B, DOSE=5E12, AKEV=200

9....COMM  --- STOP PLOTTING, START PRINTING INFORMATION ---
10....PLOT  TOTL=N
11....PRINT HEAD=Y

12....COMM  DIVE-IN IN N2 FOR 1.5 HOURS
13....STEP  TYPE=OXID, TEMP=1100, TIME=90, MODL=NIT0

14....STEP  TYPE=ETCH, TEMP=25

15....COMM  ---EXTEND GRID SPACE---
16....GRID  DYSI=0.015, DPTH=1.0, YMAX=7.0

17....COMM  DRIVE-IN FOR 15 HOURS IN 10% DRY O2
18....MODEL NAME=DRY1, PRES=.1
19....STEP  TYPE=OXID, TEMP=1100, TIME=900, MODL=DRY1

20....COMM  FIELD OXID GROWTH IN WET O2 FOR 5 HOURS
21....STEP  TYPE=OXID, TEMP=1025, TIME=300, MODL=WET0

22....STEP  TYPE=ETCH, TEMP=25

23....COMM  GATE OXIDATION AT 1000 C
24....STEP  TYPE=OXID, TEMP=1000, TIME=5, MODL=DRY0
25....STEP  TYPE=OXID, TEMP=1000, TIME=5, MODL=WET0
26....PLOT  TOTL=Y, WIND=6.
27....STEP  TYPE=OXID, TEMP=1000, TIME=5, MODL=DRY0

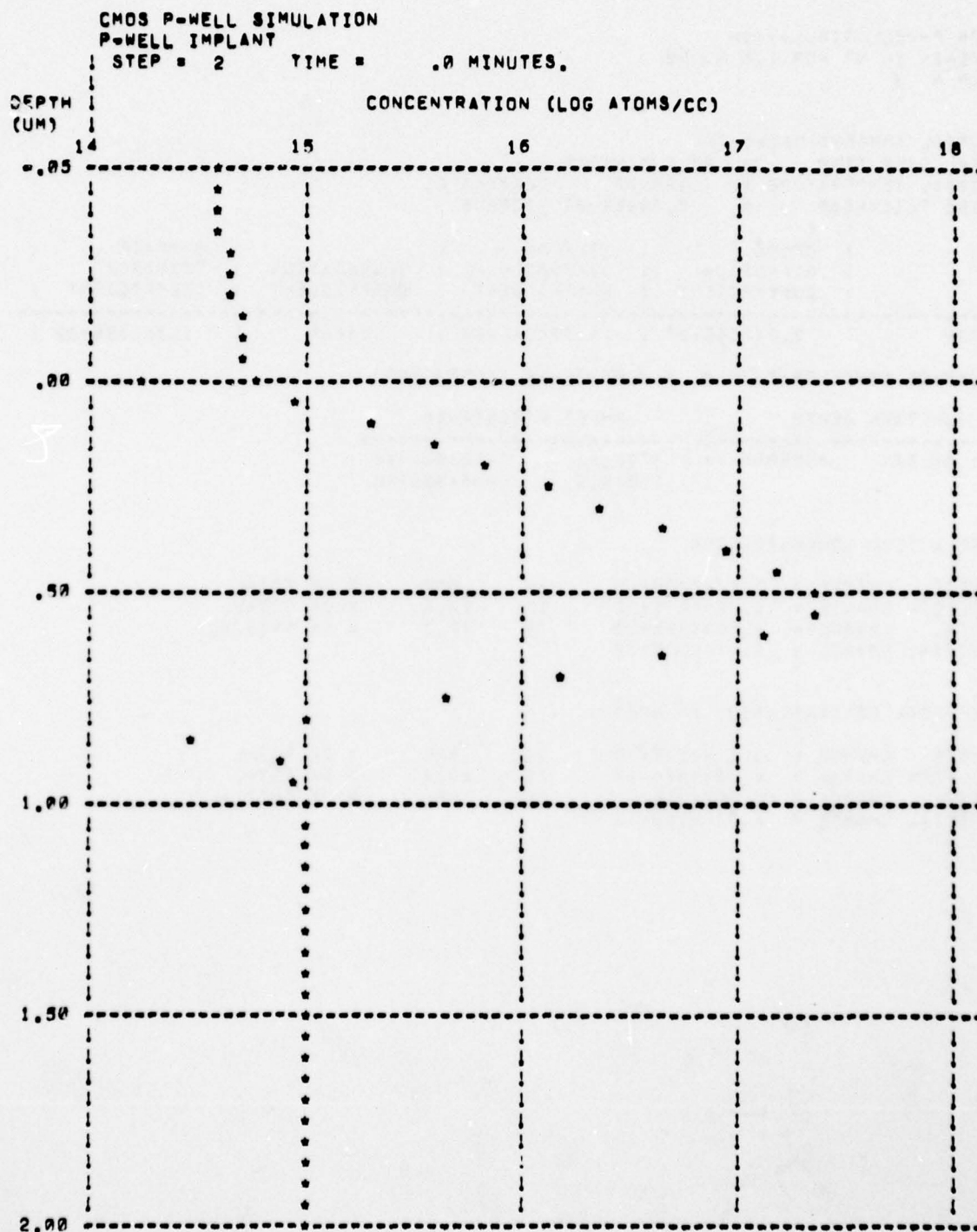
28....SAVE  FILE=PW1,TYPE=B

29....COMM  ANNEAL --- CALCULATE THRESHOLD VOLTAGE---
30....MODEL NAME=SPM1, GATE=A1, QSSQ=4E10, CBLK=1
31....STEP  TYPE=OXID, TEMP=1000, TIME=30, MODL=NIT0, MODL=SPM1

32....COMM  THRESHOLD TAILORING IMPLANT
33....MODEL NAME=SPM1, CBLK=6E15
34....STEP  TYPE=IMPL, ELEM=P, DOSE=5E11, AKEV=90, MODL=SPM1

35....END

```



CMOS P-WELL SIMULATION
 DIVE-IN IN N2 FOR 1.5 HOURS
 STEP # 3

NEUTRAL AMBIENT DRIVE-IN
 TOTAL STEP TIME = 90.0 MINUTES
 INITIAL TEMPERATURE = 1100.00 DEGREES C.
 OXIDE THICKNESS = 5.0000E-02 MICRONS

	OXIDE DIFFUSION COEFFICIENT	SILICON DIFFUSION COEFFICIENT	SEGREGATION COEFFICIENT	SURFACE TRANSPORT COEFFICIENT
BORON	2.09716E-07	8.90324E-04	.66145	1.31132E-02

SURFACE CONCENTRATION = 4.310697E+16 ATOMS/CM²

JUNCTION DEPTH	SHEET RESISTANCE
1.66157 MICRONS	3722.72 OHMS/SQUARE
	66619.9 OHMS/SQUARE

NET ACTIVE CONCENTRATION

OXIDE CHARGE	= 3.114949E+10	IS	.638	% OF TOTAL
SILICON CHARGE	= 4.854020E+12	IS	99.4	% OF TOTAL
TOTAL CHARGE	= 4.885170E+12	IS	96.3	% OF INITIAL
INITIAL CHARGE	= 5.071022E+12			

CHEMICAL CONCENTRATION OF BORON

OXIDE CHARGE	= 3.114950E+10	IS	.623	% OF TOTAL
SILICON CHARGE	= 4.966288E+12	IS	99.4	% OF TOTAL
TOTAL CHARGE	= 4.997437E+12	IS	100.	% OF INITIAL
INITIAL CHARGE	= 4.997420E+12			

CMOS P-WELL SIMULATION
 DIVE-IN IN N2 FOR 1.5 HOURS
 STEP # 4

ETCH STEP
 ETCH TEMPERATURE = 25.0 DEGREES C.
 ETCH TIME = .0 MINUTES
 ETCH RATE = .0000 MICRONS/MINUTE
 OXIDE THICKNESS = 0.0000E+00 MICRONS

SURFACE CONCENTRATION = 4.310697E+16 ATOMS/CM³

JUNCTION DEPTH		SHEET RESISTANCE	
1.66197	MICRONS	3722.72	OHMS/SQUARE
		66619.9	OHMS/SQUARE

NET ACTIVE CONCENTRATION

OXIDE CHARGE	=	0.000000E+00	IS	0.000E+00	% OF TOTAL
SILICON CHARGE	=	4.854020E+12	IS	100.0	% OF TOTAL
TOTAL CHARGE	=	4.854020E+12	IS	99.4	% OF INITIAL
INITIAL CHARGE	=	4.885170E+12			

CHEMICAL CONCENTRATION OF BORON

OXIDE CHARGE	=	0.000000E+00	IS	0.000E+00	% OF TOTAL
SILICON CHARGE	=	4.966288E+12	IS	100.0	% OF TOTAL
TOTAL CHARGE	=	4.966288E+12	IS	99.4	% OF INITIAL
INITIAL CHARGE	=	4.997437E+12			

CMOS P-WELL SIMULATION
 DRIVE-IN FOR 15 HOURS IN 10% DRY O2
 STEP # 5

OXIDATION IN DRY OXYGEN

TOTAL STEP TIME = 900.0 MINUTES
 INITIAL TEMPERATURE = 1100.00 DEGREES C.
 OXIDE THICKNESS = .1404 MICRONS

LINEAR OXIDE GROWTH RATE = 3.00741E-04 MICRONS/MINUTE
 PARABOLIC OXIDE GROWTH RATE = 3.988500E-05 MICRONS^2/MINUTE
 OXIDE GROWTH PRESSURE = 9.999999E-02 ATMOSPHERES

	OXIDE DIFFUSION COEFFICIENT	SILICON DIFFUSION COEFFICIENT	SEGREGATION COEFFICIENT	SURFACE TRANSPORT COEFFICIENT
BORON	2.09716E-07	1.23522E-03	.66145	1.31132E-02

SURFACE CONCENTRATION = 1.915271E+16 ATOMS/CM^3

JUNCTION DEPTH	SHEET RESISTANCE
4.03260 MICRONS	4067.52 OHMS/SQUARE
	19710.6 OHMS/SQUARE

NET ACTIVE CONCENTRATION

	CHARGE	IS	% OF TOTAL
OXIDE	5.003394E+11	10.9	% OF TOTAL
SILICON	4.001520E+12	89.1	% OF TOTAL
TOTAL	4.501859E+12	94.4	% OF INITIAL
INITIAL	4.854124E+12		

CHEMICAL CONCENTRATION OF BORON

	CHARGE	IS	% OF TOTAL
OXIDE	5.003394E+11	10.4	% OF TOTAL
SILICON	4.311637E+12	89.6	% OF TOTAL
TOTAL	4.811976E+12	96.9	% OF INITIAL
INITIAL	4.986391E+12		

CMOS P-WELL SIMULATION
 FIELD OXID GROWTH IN WET O2 FOR 5HOURS
 STEP # 6

OXIDATION IN WET OXYGEN

TOTAL STEP TIME = 300.0 MINUTES
 INITIAL TEMPERATURE = 1025.00 DEGREES C.
 OXIDE THICKNESS = 1.203 MICRONS

LINEAR OXIDE GROWTH RATE = 2.116309E-02 MICRONS/MINUTE
 PARABOLIC OXIDE GROWTH RATE = 5.718539E-03 MICRONS^2/MINUTE
 OXIDE GROWTH PRESSURE = .842105 ATMOSPHERES

	OXIDE DIFFUSION COEFFICIENT	SILICON DIFFUSION COEFFICIENT	SEGREGATION COEFFICIENT	SURFACE TRANSPORT COEFFICIENT
BORON	3.74197E-08	3.18287E-04	.41393	3.98494E-03

SURFACE CONCENTRATION = 3.349655E+15 ATOMS/CM^3

JUNCTION DEPTH	SHEET RESISTANCE
3.68458 MICRONS	5788.51 OHMS/SQUARE
	21049.1 OHMS/SQUARE

NET ACTIVE CONCENTRATION

OXIDE CHARGE	= 1.725380E+12	IS	37.6	% OF TOTAL
SILICON CHARGE	= 2.859700E+12	IS	62.4	% OF TOTAL
TOTAL CHARGE	= 4.585079E+12	IS	100.	% OF INITIAL
INITIAL CHARGE	= 4.581859E+12			

CHEMICAL CONCENTRATION OF BORON

OXIDE CHARGE	= 1.725380E+12	IS	36.0	% OF TOTAL
SILICON CHARGE	= 3.071598E+12	IS	64.0	% OF TOTAL
TOTAL CHARGE	= 4.796978E+12	IS	99.7	% OF INITIAL
INITIAL CHARGE	= 4.811976E+12			

CMOS P-WELL SIMULATION
FIELD OXID GROWTH IN WET O2 FOR 5HOURS
STEP # 7

ETCH STEP
ETCH TEMPERATURE = 25.0 DEGREES C.
ETCH TIME = .0 MINUTES
ETCH RATE = .0000 MICRONS/MINUTE
OXIDE THICKNESS = 0.0000E+00 MICRONS

SURFACE CONCENTRATION = 3.349655E+15 ATOMS/CM²3

JUNCTION DEPTH		SHEET RESISTANCE
3.68457	MICRONS	5788.55 OHMS/SQUARE
		21849.1 OHMS/SQUARE

NET ACTIVE CONCENTRATION

OXIDE CHARGE =	0.000000E+00	IS	0.000E+00	% OF TOTAL
SILICON CHARGE =	2.859700E+12	IS	100.0	% OF TOTAL
TOTAL CHARGE =	2.859700E+12	IS	62.4	% OF INITIAL
INITIAL CHARGE =	4.585079E+12			

CHEMICAL CONCENTRATION OF BORON

OXIDE CHARGE =	0.000000E+00	IS	0.000E+00	% OF TOTAL
SILICON CHARGE =	3.071598E+12	IS	100.0	% OF TOTAL
TOTAL CHARGE =	3.071598E+12	IS	64.0	% OF INITIAL
INITIAL CHARGE =	4.798978E+12			

CMOS P-WELL SIMULATION
GATE OXIDATION AT 1000 C
STEP # 8

OXIDATION IN DRY OXYGEN

TOTAL STEP TIME = 5.0 MINUTES
INITIAL TEMPERATURE = 1000.000 DEGREES C.
OXIDE THICKNESS = 2.0675E-02 MICRONS

LINEAR OXIDE GROWTH RATE = 8.019060E-03 MICRONS/MINUTE
PARABOLIC OXIDE GROWTH RATE = 1.765088E-04 MICRONS²/MINUTE
OXIDE GROWTH PRESSURE = 1.00000 ATMOSPHERES

	OXIDE DIFFUSION COEFFICIENT	SILICON DIFFUSION COEFFICIENT	SEGREGATION COEFFICIENT	SURFACE TRANSPORT COEFFICIENT
BORON	2.01368E-08	2.03949E-04	.34974	2.52626E-03

SURFACE CONCENTRATION = 1.724042E+15 ATOMS/CM²

JUNCTION DEPTH	SHEET RESISTANCE
3.67469 MICRONS	5821.01 OHMS/SQUARE
	21001.5 OHMS/SQUARE

NET ACTIVE CONCENTRATION

OXIDE CHARGE = 1.113799E+10	IS	.390	% OF TOTAL
SILICON CHARGE = 2.844184E+12	IS	99.6	% OF TOTAL
TOTAL CHARGE = 2.855322E+12	IS	99.8	% OF INITIAL
INITIAL CHARGE = 2.859700E+12			

CHEMICAL CONCENTRATION OF BORON

OXIDE CHARGE = 1.113799E+10	IS	.363	% OF TOTAL
SILICON CHARGE = 3.055481E+12	IS	99.6	% OF TOTAL
TOTAL CHARGE = 3.066619E+12	IS	99.8	% OF INITIAL
INITIAL CHARGE = 3.071598E+12			

CMOS P-WELL SIMULATION
GATE OXIDATION AT 1000 C
STEP # 9

OXIDATION IN WET OXYGEN

TOTAL STEP TIME = 5.0 MINUTES
INITIAL TEMPERATURE = 1000.000 DEGREES C.
OXIDE THICKNESS = 7.8622E-02 MICRONS

LINEAR OXIDE GROWTH RATE = 1.499959E-02 MICRONS/MINUTE
PARABOLIC OXIDE GROWTH RATE = 5.061528E-03 MICRONS²/MINUTE
OXIDE GROWTH PRESSURE = .842105 ATMOSPHERES

	OXIDE DIFFUSION COEFFICIENT	SILICON DIFFUSION COEFFICIENT	SEGREGATION COEFFICIENT	SURFACE TRANSPORT COEFFICIENT
BORON	2.01368E-08	2.03949E-04	.34974	2.52626E-03

SURFACE CONCENTRATION = 6.758076E+14 ATOMS/CM²

JUNCTION DEPTH	SHEET RESISTANCE
3.65247 MICRONS	5872.50 OHMS/SQUARE
	21077.7 OHMS/SQUARE

NET ACTIVE CONCENTRATION

OXIDE CHARGE	SILICON CHARGE	TOTAL CHARGE	INITIAL CHARGE	IS	% OF TOTAL	% OF INITIAL
3.422924E+10	2.821365E+12	2.855594E+12	2.855322E+12	1.20	98.8	100.

CHEMICAL CONCENTRATION OF BORON

OXIDE CHARGE	SILICON CHARGE	TOTAL CHARGE	INITIAL CHARGE	IS	% OF TOTAL	% OF INITIAL
3.422924E+10	3.030403E+12	3.064632E+12	3.066619E+12	1.12	98.9	99.9

CMOS P-WELL SIMULATION
GATE OXIDATION AT 1000 C
STEP # 10

OXIDATION IN DRY OXYGEN

TOTAL STEP TIME = 5.0 MINUTES
INITIAL TEMPERATURE = 1000.000 DEGREES C.
OXIDE THICKNESS = 8.0946E-02 MICRONS

LINEAR OXIDE GROWTH RATE = 8.019060E-04 MICRONS/MINUTE
PARABOLIC OXIDE GROWTH RATE = 1.765125E-04 MICRONS²/MINUTE
OXIDE GROWTH PRESSURE = 1.00000 ATMOSPHERES

	OXIDE DIFFUSION COEFFICIENT	SILICON DIFFUSION COEFFICIENT	SEGREGATION COEFFICIENT	SURFACE TRANSPORT COEFFICIENT
BORON	2.01368E-08	2.03949E-04	.34974	2.52626E-03

SURFACE CONCENTRATION = 3.119767E+15 ATOMS/CM²

JUNCTION DEPTH	SHEET RESISTANCE
3.65270 MICRONS	5082.82 OHMS/SQUARE
	21087.8 OHMS/SQUARE

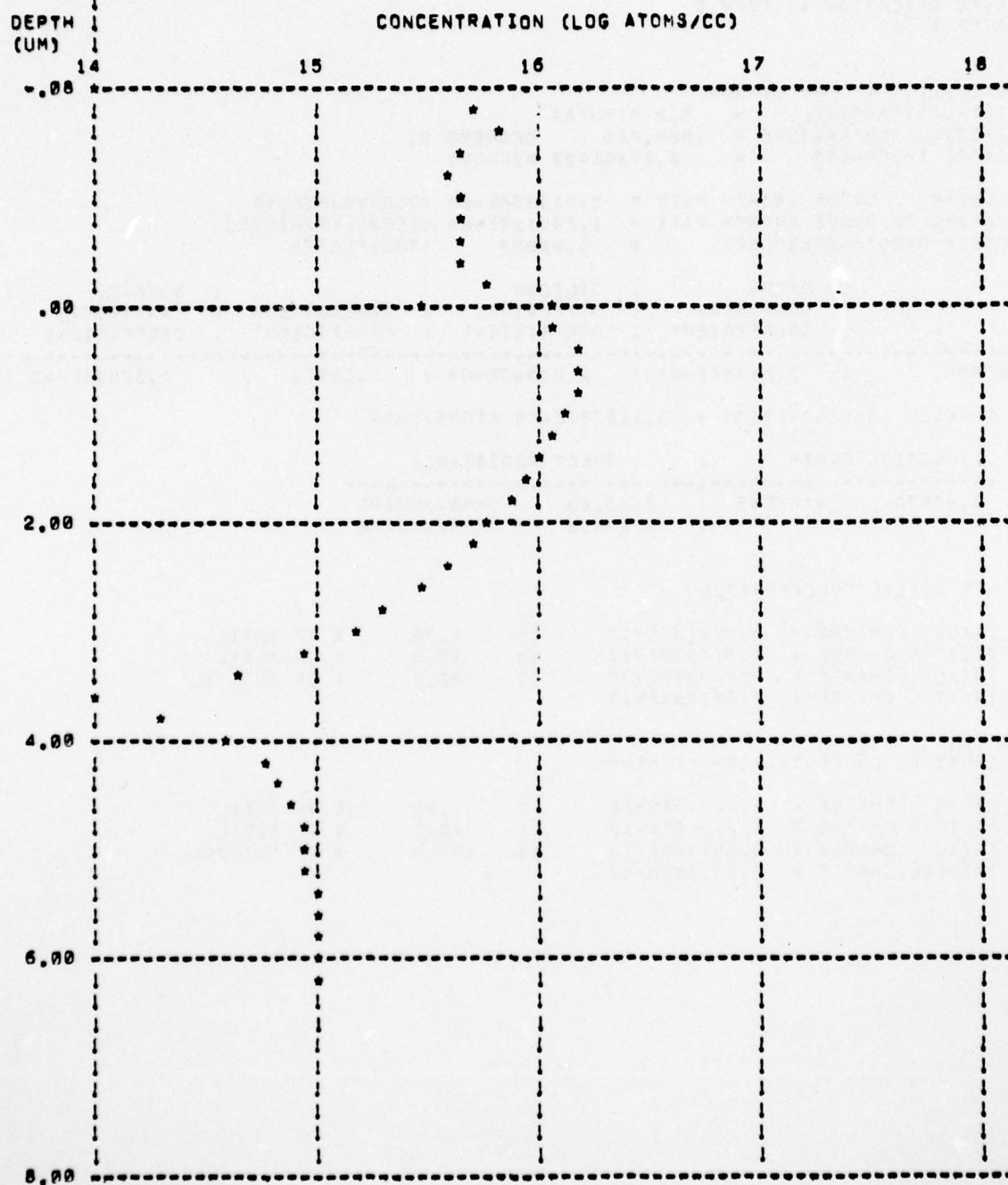
NET ACTIVE CONCENTRATION

OXIDE CHARGE = 3.929135E+10	IS	1.38	% OF TOTAL
SILICON CHARGE = 2.815937E+12	IS	98.6	% OF TOTAL
TOTAL CHARGE = 2.855228E+12	IS	100.0	% OF INITIAL
INITIAL CHARGE = 2.855594E+12			

CHEMICAL CONCENTRATION OF BORON

OXIDE CHARGE = 3.929135E+10	IS	1.28	% OF TOTAL
SILICON CHARGE = 3.025167E+12	IS	98.7	% OF TOTAL
TOTAL CHARGE = 3.064459E+12	IS	100.0	% OF INITIAL
INITIAL CHARGE = 3.064632E+12			

CMOS P-WELL SIMULATION
GATE OXIDATION AT 1000 C
STEP = 10 TIME = 5.0 MINUTES.



CMOS P-WELL SIMULATION
 ANNEAL --- CALCULATE THRESHOLD VOLTAGE---
 STEP # 11

NEUTRAL AMBIENT DRIVE-IN
 TOTAL STEP TIME = 30.0 MINUTES
 INITIAL TEMPERATURE = 1000.000 DEGREES C.
 OXIDE THICKNESS = 8.0046E-02 MICRONS

	OXIDE DIFFUSION COEFFICIENT	SILICON DIFFUSION COEFFICIENT	SEGREGATION COEFFICIENT	SURFACE TRANSPORT COEFFICIENT
BORON	2.01368E-08	9.16197E-05	.34974	2.52626E-03

SURFACE CONCENTRATION = 5.656077E+15 ATOMS/CM+3

GATE MATERIAL = ALUMINUM SILICON UNDER GATE = P - TYPE
 OXIDE THICKNESS = 809.5 ANG. CAPACITANCE/AREA = 4.26E-04 PF/UM2
 THRESHOLD VOLTAGE = .58 VOLTS AT SURFACE STATES = 4.00E+10

JUNCTION DEPTH	SHEET RESISTANCE
3.65608 MICRONS	5887.67 OHMS/SQUARE
	21109.7 OHMS/SQUARE

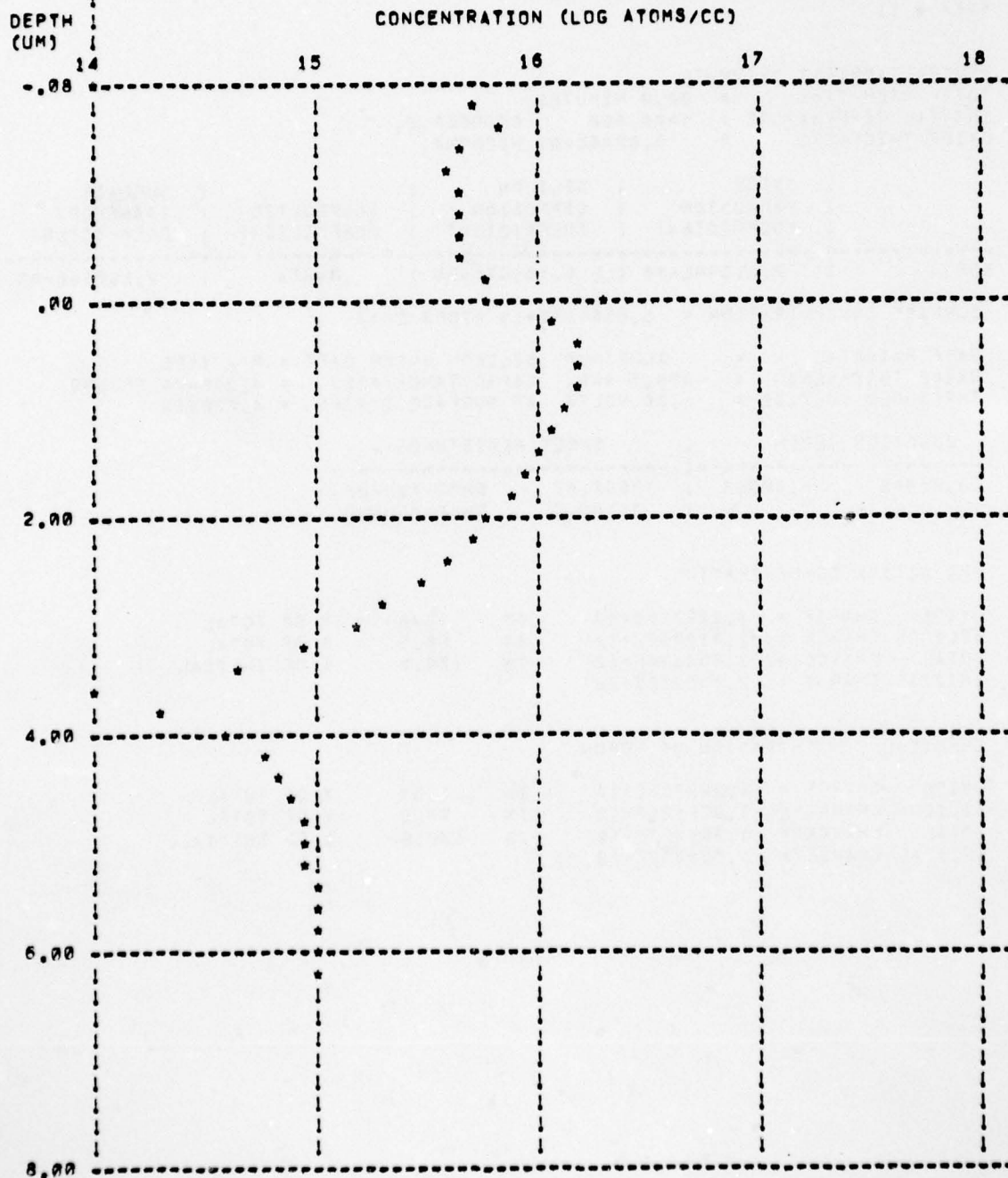
NET ACTIVE CONCENTRATION

OXIDE CHARGE = 4.229726E+10	IS	1.48	% OF TOTAL
SILICON CHARGE = 2.812097E+12	IS	98.5	% OF TOTAL
TOTAL CHARGE = 2.854394E+12	IS	100.0	% OF INITIAL
INITIAL CHARGE = 2.855228E+12			

CHEMICAL CONCENTRATION OF BORON

OXIDE CHARGE = 4.229726E+10	IS	1.38	% OF TOTAL
SILICON CHARGE = 3.022125E+12	IS	98.6	% OF TOTAL
TOTAL CHARGE = 3.064422E+12	IS	100.0	% OF INITIAL
INITIAL CHARGE = 3.064459E+12			

CMOS P-WELL SIMULATION
 ANNEAL --- CALCULATE THRESHOLD VOLTAGE---
 STEP = 11 TIME = 30.0 MINUTES.



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SUPREM II -- A PROGRAM FOR IC PROCESS MODELING AND SIMULATION.(U)
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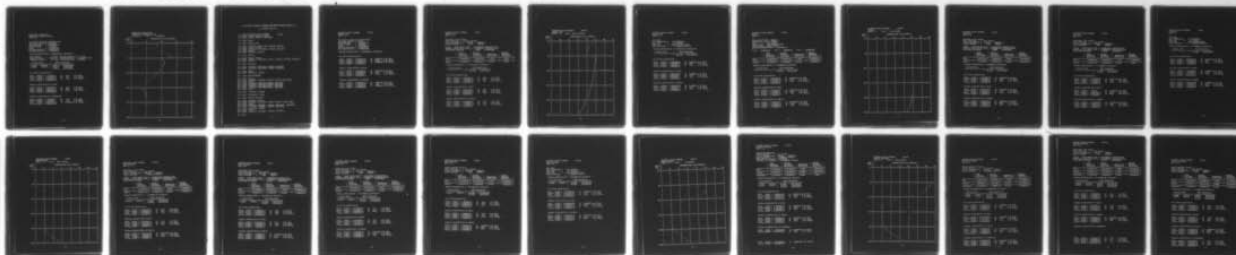
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CMOS P-WELL SIMULATION
THRESHOLD TAILORING IMPLANT
STEP # 12

ION IMPLANT (GAUSSIAN APPROXIMATION)
IMPLANTED IMPURITY = PHOSPHORUS
IMPLANTED DOSE = 5.000000E+11
IMPLANT ENERGY = 90.0000
RANGE = 9.664024E-02
STANDARD DEVIATION = 4.174892E-02
PEAK CONCENTRATION = 5.023804E+16

SURFACE CONCENTRATION = -4.060335E+16 ATOMS/CM³

GATE MATERIAL = ALUMINUM SILICON UNDER GATE = N - TYPE
OXIDE THICKNESS = 809.5 ANG. CAPACITANCE/AREA = 4.26E-04 PF/UM²
THRESHOLD VOLTAGE = .15 VOLTS AT SURFACE STATES = 4.00E+10

JUNCTION DEPTH		SHEET RESISTANCE	
.101351	MICRONS	24786.9	OHMS/SQUARE
3.65608	MICRONS	6092.49	OHMS/SQUARE
		21109.4	OHMS/SQUARE

NET ACTIVE CONCENTRATION

OXIDE CHARGE	= 1.101700E+11	IS	3.79	% OF TOTAL
SILICON CHARGE	= 3.002378E+12	IS	96.2	% OF TOTAL
TOTAL CHARGE	= 3.120549E+12	IS	100.	% OF INITIAL
INITIAL CHARGE	= 2.854394E+12			

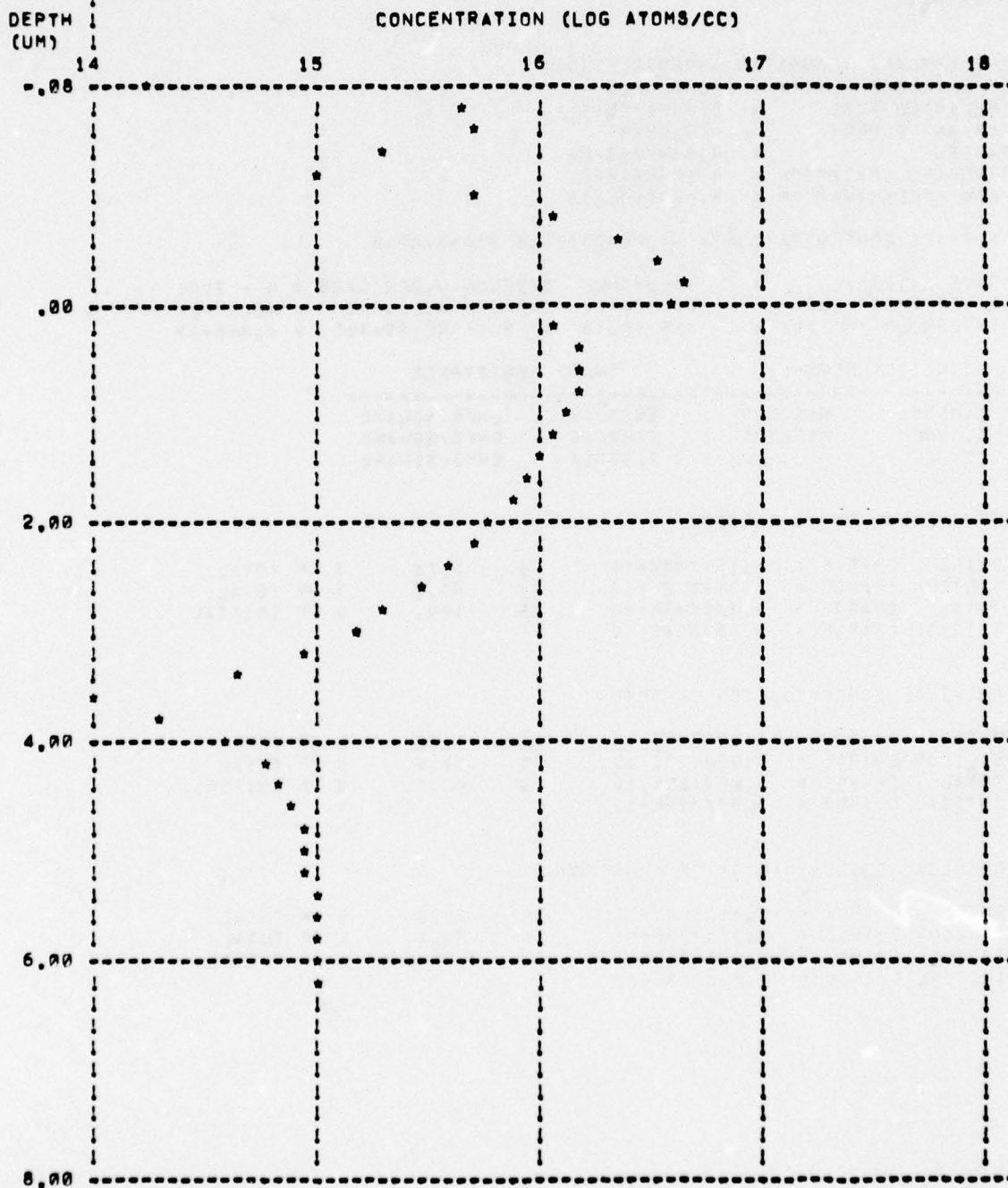
CHEMICAL CONCENTRATION OF BORON

OXIDE CHARGE	= 4.229726E+10	IS	1.30	% OF TOTAL
SILICON CHARGE	= 3.022125E+12	IS	98.6	% OF TOTAL
TOTAL CHARGE	= 3.064422E+12	IS	100.0	% OF INITIAL
INITIAL CHARGE	= 3.064422E+12			

CHEMICAL CONCENTRATION OF PHOSPHORUS

OXIDE CHARGE	= 1.413504E+11	IS	28.3	% OF TOTAL
SILICON CHARGE	= 3.583073E+11	IS	71.7	% OF TOTAL
TOTAL CHARGE	= 4.996577E+11	IS	0.000E+00	% OF INITIAL
INITIAL CHARGE	= 0.000000E+00			

CMOS P-WELL SIMULATION
 THRESHOLD TAILORING IMPLANT
 STEP = 12 TIME = .0 MINUTES.



*** STANFORD UNIVERSITY PROCESS ENGINEERING MODELS PROGRAM ***

*** VERSION 0-02 ***

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1....TITLE STANFORD KITCHIP PROCESS          6/5/78
2....GRID YMAX=5, DPTH=1, DYSI=.01
3....SUBS ELEM=B ,CONC=1E15 ,ORNT=100

4....PRINT HEAD=Y

5....COMM BURIED LAYER

6....STEP TYPE=IMPL, DOSE=1.5E15, AKEV=30, ELEM=AS
7....PLOT TOTL=Y, WIND=4
8....STEP TYPE=OXID, TEMP=1250, TIME=100, MODL=DRY0
9....PLOT TOTL=N
10....STEP TYPE=ETCH, TEMP=25

11....COMM EPITAXY

12....PLOT TOTL=Y, WIND=8
13....STEP TYPE=EPIT, TEMP=1000, TIME=11, GRTE=.5, ELEM=AS, CONC=1E15
14....PLOT TOTL=N

15....COMM ISOLATION

16....STEP TYPE=OXID, TEMP=1100, TIME=60, MODL=DRY0
17....STEP TYPE=OXID, TEMP=1200, TIME=90, MODL=DRY0

18....PLOT TOTL=Y
19....STEP TYPE=ETCH, TEMP=25

20....COMM BASE DIFFUSION

21....PLOT WIND=4
22....STEP TYPE=PDEP ,TEMP=950 ,TIME=30 ,ELEM=B ,CONC=1.2E20
23....PLOT TOTL=N
24....STEP TYPE=OXID ,TEMP=1000,TIME=45 ,MODL=DRY0
25....STEP TYPE=OXID ,TEMP=1000,TIME=60 ,MODL=WET0
26....STEP TYPE=OXID ,TEMP=1000,TIME=5 ,MODL=DRY0
27....STEP TYPE=OXID ,TEMP=1000,TIME=10 ,MODL=NIT0
28....PLOT TOTL=Y

29....STEP TYPE=ETCH ,TEMP=25

30....SAVE FILE=EBNCF ,TYPE=B

31....COMM EMITTER DIFFUSION

32....MODEL NAME=MPH2 ,STC0=0
33....STEP TYPE=PDEP ,TEMP=1025 ,TIME=33 ,ELEM=P ,CONC=1.15E21
34....PLOT TOTL=N
35....STEP TYPE=OXID ,TEMP=900 ,TIME=10 ,MODL=NIT0 ,MODL=MPH2
36....STEP TYPE=OXID ,TEMP=900 ,TIME=10 ,MODL=WET0
37....SAVE FILE=EBNCL ,TYPE=B
38....PLOT TOTL=Y
39....STEP TYPE=OXID ,TEMP=900 ,TIME=10 ,MODL=NIT0

40....END

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STANFORD KITCHIP PROCESS
BURIED LAYER
STEP # 1

6/5/78

ION IMPLANT (GAUSSIAN APPROXIMATION)
IMPLANTED IMPURITY = ARSENIC
IMPLANTED DOSE = $1.500000E+15$
IMPLANT ENERGY = 30.0000
RANGE = $2.688498E-02$
STANDARD DEVIATION = $7.682185E-03$
PEAK CONCENTRATION = $7.789626E+20$

SURFACE CONCENTRATION = $9.970628E+14$ ATOMS/CM²

NET ACTIVE CONCENTRATION

OXIDE CHARGE =	$0.000000E+00$	IS	$0.000E+00$	% OF TOTAL
SILICON CHARGE =	$1.449207E+15$	IS	100.0	% OF TOTAL
TOTAL CHARGE =	$1.449207E+15$	IS	$2.898E+05$	% OF INITIAL
INITIAL CHARGE =	$5.000000E+11$			

CHEMICAL CONCENTRATION OF BORON

OXIDE CHARGE =	$0.000000E+00$	IS	$0.000E+00$	% OF TOTAL
SILICON CHARGE =	$5.000000E+11$	IS	100.0	% OF TOTAL
TOTAL CHARGE =	$5.000000E+11$	IS	100.0	% OF INITIAL
INITIAL CHARGE =	$5.000000E+11$			

CHEMICAL CONCENTRATION OF ARSENIC

OXIDE CHARGE =	$0.000000E+00$	IS	$0.000E+00$	% OF TOTAL
SILICON CHARGE =	$1.448723E+15$	IS	100.	% OF TOTAL
TOTAL CHARGE =	$1.448723E+15$	IS	$0.000E+00$	% OF INITIAL
INITIAL CHARGE =	$0.000000E+00$			

STANFORD KITCHIP PROCESS
BURIED LAYER
STEP # 2

6/5/78

OXIDATION IN DRY OXYGEN

TOTAL STEP TIME = 180.0 MINUTES
INITIAL TEMPERATURE = 1250.00 DEGREES C.
OXIDE THICKNESS = .4177 MICRONS

LINEAR OXIDE GROWTH RATE = 1.577485E-02 MICRONS/MINUTE
PARABOLIC OXIDE GROWTH RATE = 1.113008E-03 MICRONS²/MINUTE
OXIDE GROWTH PRESSURE = 1.00000 ATMOSPHERES

	OXIDE DIFFUSION COEFFICIENT	SILICON DIFFUSION COEFFICIENT	SEGREGATION COEFFICIENT	SURFACE TRANSPORT COEFFICIENT
BORON	3.95869E-06	1.68161E-02	1.4706	.10339
ARSENIC	6.93186E-07	4.55201E-03	10.0000	.23421

SURFACE CONCENTRATION = -7.765171E+18 ATOMS/CM³

JUNCTION DEPTH	SHEET RESISTANCE
	28.4198 OHMS/SQUARE

NET ACTIVE CONCENTRATION

OXIDE CHARGE	= 8.700562E+13	IS	5.92	% OF TOTAL
SILICON CHARGE	= 1.382555E+15	IS	94.1	% OF TOTAL
TOTAL CHARGE	= 1.469560E+15	IS	101.	% OF INITIAL
INITIAL CHARGE	= 1.449207E+15			

CHEMICAL CONCENTRATION OF BORON

OXIDE CHARGE	= 2.784715E+10	IS	5.60	% OF TOTAL
SILICON CHARGE	= 4.698372E+11	IS	94.4	% OF TOTAL
TOTAL CHARGE	= 4.976843E+11	IS	99.5	% OF INITIAL
INITIAL CHARGE	= 5.000000E+11			

CHEMICAL CONCENTRATION OF ARSENIC

OXIDE CHARGE	= 8.703345E+13	IS	5.92	% OF TOTAL
SILICON CHARGE	= 1.383732E+15	IS	94.1	% OF TOTAL
TOTAL CHARGE	= 1.470066E+15	IS	101.	% OF INITIAL
INITIAL CHARGE	= 1.448723E+15			

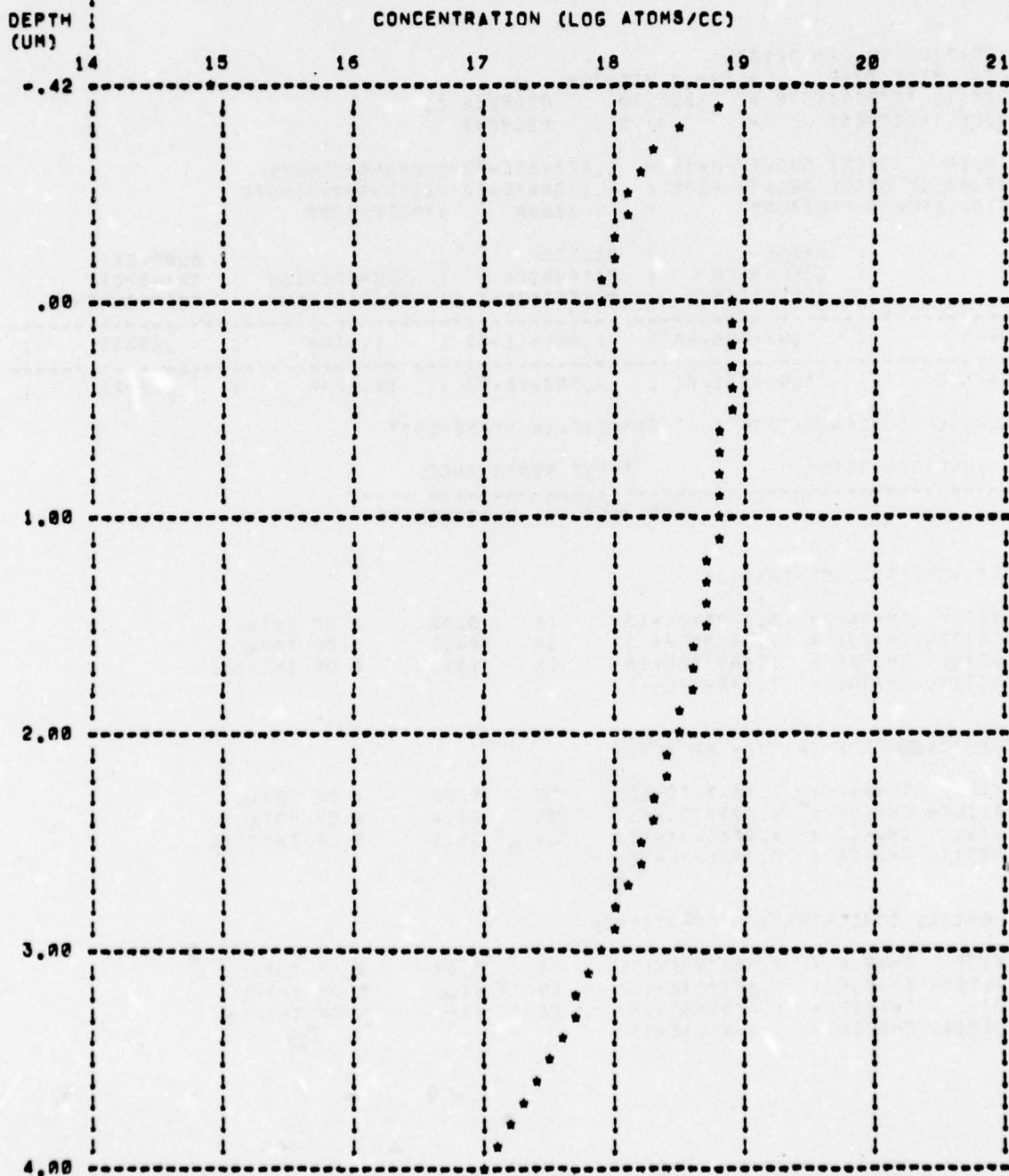
STANFORD KITCHIP PROCESS

6/5/78

BURIED LAYER

STEP = 2

TIME = 180.0 MINUTES.



STANFORD KITCHIP PROCESS
BURIED LAYER
STEP # 3

6/5/78

ETCH STEP
ETCH TEMPERATURE = 25.0 DEGREES C.
ETCH TIME = .0 MINUTES
ETCH RATE = .0000 MICRONS/MINUTE
OXIDE THICKNESS = 0.0000E+00 MICRONS

SURFACE CONCENTRATION = -7.765171E+18 ATOMS/CM³

JUNCTION DEPTH	SHEET RESISTANCE
----- -----	----- -----
1	1
28.4198	OHMS/SQUARE

NET ACTIVE CONCENTRATION

OXIDE CHARGE = 0.000000E+00	IS 0.000E+00 % OF TOTAL
SILICON CHARGE = 1.382555E+15	IS 100.0 % OF TOTAL
TOTAL CHARGE = 1.382555E+15	IS 94.1 % OF INITIAL
INITIAL CHARGE = 1.469560E+15	

CHEMICAL CONCENTRATION OF BORON

OXIDE CHARGE = 0.000000E+00	IS 0.000E+00 % OF TOTAL
SILICON CHARGE = 4.698372E+11	IS 100.0 % OF TOTAL
TOTAL CHARGE = 4.698372E+11	IS 94.4 % OF INITIAL
INITIAL CHARGE = 4.976843E+11	

CHEMICAL CONCENTRATION OF ARSENIC

OXIDE CHARGE = 0.000000E+00	IS 0.000E+00 % OF TOTAL
SILICON CHARGE = 1.383032E+15	IS 100.0 % OF TOTAL
TOTAL CHARGE = 1.383032E+15	IS 94.1 % OF INITIAL
INITIAL CHARGE = 1.470066E+15	

STANFORD KITCHIP PROCESS
 EPITAXY
 STEP # 4

6/5/78

EPI-LAYER IMPURITY = ARSENIC
 TEMPERATURE = 1000.0 DEGREES C
 TIME = 11.0 MINUTES
 GROWTH RATE = .500 MICRONS/MINUTE
 SILICON ADDED = 5.5000 MICRONS
 GAS-PHASE CONCENTRATION = 1.000000E+15

FAUT = .000000E+00 FRAC = .000000E+00 FINT = .000000E+00

	OXIDE DIFFUSION COEFFICIENT	SILICON DIFFUSION COEFFICIENT	SEGREGATION COEFFICIENT	SURFACE TRANSPORT COEFFICIENT
BORON	3.95869E-06	9.16197E-05	1.4706	2.52626E-03
ARSENIC	6.93186E-07	1.01692E-05	10.0000	1.19298E-02

SURFACE CONCENTRATION = -1.000000E+15 ATOMS/CM³

JUNCTION DEPTH	SHEET RESISTANCE
	28.2615 OHMS/SQUARE

NET ACTIVE CONCENTRATION

OXIDE CHARGE	= 0.000000E+00	IS	0.000E+00	% OF TOTAL
SILICON CHARGE	= 1.379372E+15	IS	100.0	% OF TOTAL
TOTAL CHARGE	= 1.379372E+15	IS	99.8	% OF INITIAL
INITIAL CHARGE	= 1.382555E+15			

CHEMICAL CONCENTRATION OF BORON

OXIDE CHARGE	= 0.000000E+00	IS	0.000E+00	% OF TOTAL
SILICON CHARGE	= 4.702629E+11	IS	100.0	% OF TOTAL
TOTAL CHARGE	= 4.702629E+11	IS	100.	% OF INITIAL
INITIAL CHARGE	= 4.698372E+11			

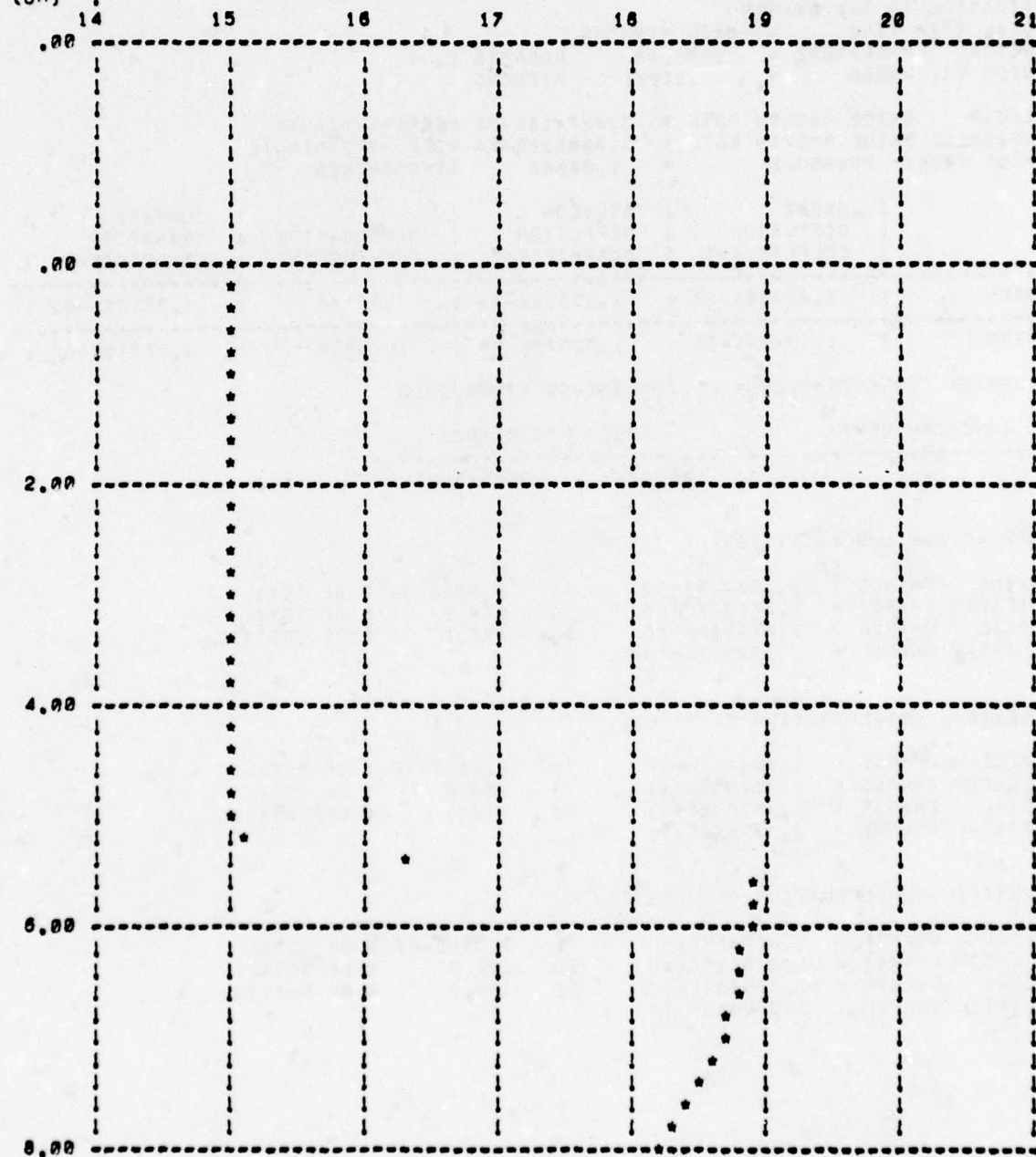
CHEMICAL CONCENTRATION OF ARSENIC

OXIDE CHARGE	= 0.000000E+00	IS	0.000E+00	% OF TOTAL
SILICON CHARGE	= 1.379050E+15	IS	100.0	% OF TOTAL
TOTAL CHARGE	= 1.379050E+15	IS	99.9	% OF INITIAL
INITIAL CHARGE	= 1.383032E+15			

6/5/78

DEPTH
(UM)

CONCENTRATION (LOG ATOMS/CC)



STANFORD KITCHIP PROCESS
ISOLATION
STEP # 5

6/5/78

OXIDATION IN DRY OXYGEN

TOTAL STEP TIME = 60.0 MINUTES
INITIAL TEMPERATURE = 1100.00 DEGREES C.
OXIDE THICKNESS = .1104 MICRONS

LINEAR OXIDE GROWTH RATE = 3.007418E-03 MICRONS/MINUTE
PARABOLIC OXIDE GROWTH RATE = 3.986828E-04 MICRONS²/MINUTE
OXIDE GROWTH PRESSURE = 1.00000 ATMOSPHERES

	OXIDE DIFFUSION COEFFICIENT	SILICON DIFFUSION COEFFICIENT	SEGREGATION COEFFICIENT	SURFACE TRANSPORT COEFFICIENT
BORON	2.09716E-07	1.23522E-03	.66145	1.31132E-02
ARSENIC	1.18402E-08	1.52575E-04	10.0000	4.47011E-02

SURFACE CONCENTRATION = -1.365323E+15 ATOMS/CM³

JUNCTION DEPTH	SHEET RESISTANCE
	27.4748 OHMS/SQUARE

NET ACTIVE CONCENTRATION

OXIDE CHARGE	SILICON CHARGE	TOTAL CHARGE	INITIAL CHARGE	IS	% OF TOTAL	% OF INITIAL
1.360439E+09	1.379328E+15	1.379330E+15	1.379372E+15	9.863E-05	100.0	100.0

CHEMICAL CONCENTRATION OF BORON

OXIDE CHARGE	SILICON CHARGE	TOTAL CHARGE	INITIAL CHARGE	IS	% OF TOTAL	% OF INITIAL
4.454211E-10	4.702636E+11	4.702636E+11	4.702629E+11	9.472E-20	100.0	100.0

CHEMICAL CONCENTRATION OF ARSENIC

OXIDE CHARGE	SILICON CHARGE	TOTAL CHARGE	INITIAL CHARGE	IS	% OF TOTAL	% OF INITIAL
1.360439E+09	1.379815E+15	1.379817E+15	1.379850E+15	9.860E-05	100.0	100.0

STANFORD KITCHIP PROCESS
ISOLATION
STEP # 6

6/5/78

OXIDATION IN DRY OXYGEN

TOTAL STEP TIME = 90.0 MINUTES
INITIAL TEMPERATURE = 1200.00 DEGREES C.
OXIDE THICKNESS = .2674 MICRONS

LINEAR OXIDE GROWTH RATE = 9.425977E-03 MICRONS/MINUTE
PARABOLIC OXIDE GROWTH RATE = 8.088042E-04 MICRONS²/MINUTE
OXIDE GROWTH PRESSURE = 1.00000 ATMOSPHERES

	OXIDE DIFFUSION COEFFICIENT	SILICON DIFFUSION COEFFICIENT	SEGREGATION COEFFICIENT	SURFACE TRANSPORT COEFFICIENT
BORON	1.58896E-06	7.26316E-03	1.1473	5.44300E-02
ARSENIC	1.95738E-07	1.58489E-03	10.0000	.14000

SURFACE CONCENTRATION = -1.199782E+15 ATOMS/CM²3

JUNCTION DEPTH	SHEET RESISTANCE
	24.7982 OHMS/SQUARE

NET ACTIVE CONCENTRATION

OXIDE CHARGE = 3.329525E+09	IS 2.414E-04 % OF TOTAL
SILICON CHARGE = 1.379357E+15	IS 100.0 % OF TOTAL
TOTAL CHARGE = 1.379360E+15	IS 100. % OF INITIAL
INITIAL CHARGE = 1.379330E+15	

CHEMICAL CONCENTRATION OF BORON

OXIDE CHARGE = 19582.6	IS 4.165E-06 % OF TOTAL
SILICON CHARGE = 4.702171E+11	IS 100.0 % OF TOTAL
TOTAL CHARGE = 4.702172E+11	IS 100.0 % OF INITIAL
INITIAL CHARGE = 4.702636E+11	

CHEMICAL CONCENTRATION OF ARSENIC

OXIDE CHARGE = 3.329545E+09	IS 2.413E-04 % OF TOTAL
SILICON CHARGE = 1.379831E+15	IS 100.0 % OF TOTAL
TOTAL CHARGE = 1.379834E+15	IS 100. % OF INITIAL
INITIAL CHARGE = 1.379817E+15	

STANFORD KITCHIP PROCESS
ISOLATION
STEP # 7

6/5/78

ETCH STEP
ETCH TEMPERATURE = 25.0 DEGREES C.
ETCH TIME = .0 MINUTES
ETCH RATE = .0000 MICRONS/MINUTE
OXIDE THICKNESS = 0.0000E+00 MICRONS

SURFACE CONCENTRATION = -1.199782E+15 ATOMS/CM³

JUNCTION DEPTH	1	SHEET RESISTANCE
-----	1	-----
	24.7981	OHMS/SQUARE

NET ACTIVE CONCENTRATION

OXIDE CHARGE =	0.000000E+00	IS	0.000E+00	% OF TOTAL
SILICON CHARGE =	1.379353E+15	IS	100.0	% OF TOTAL
TOTAL CHARGE =	1.379353E+15	IS	100.0	% OF INITIAL
INITIAL CHARGE =	1.379360E+15			

CHEMICAL CONCENTRATION OF BORON

OXIDE CHARGE =	0.000000E+00	IS	0.000E+00	% OF TOTAL
SILICON CHARGE =	4.702186E+11	IS	100.0	% OF TOTAL
TOTAL CHARGE =	4.702186E+11	IS	100.	% OF INITIAL
INITIAL CHARGE =	4.702172E+11			

CHEMICAL CONCENTRATION OF ARSENIC

OXIDE CHARGE =	0.000000E+00	IS	0.000E+00	% OF TOTAL
SILICON CHARGE =	1.379827E+15	IS	100.0	% OF TOTAL
TOTAL CHARGE =	1.379827E+15	IS	100.0	% OF INITIAL
INITIAL CHARGE =	1.379834E+15			

STANFORD KITCHIP PROCESS

6/5/78

ISOLATION

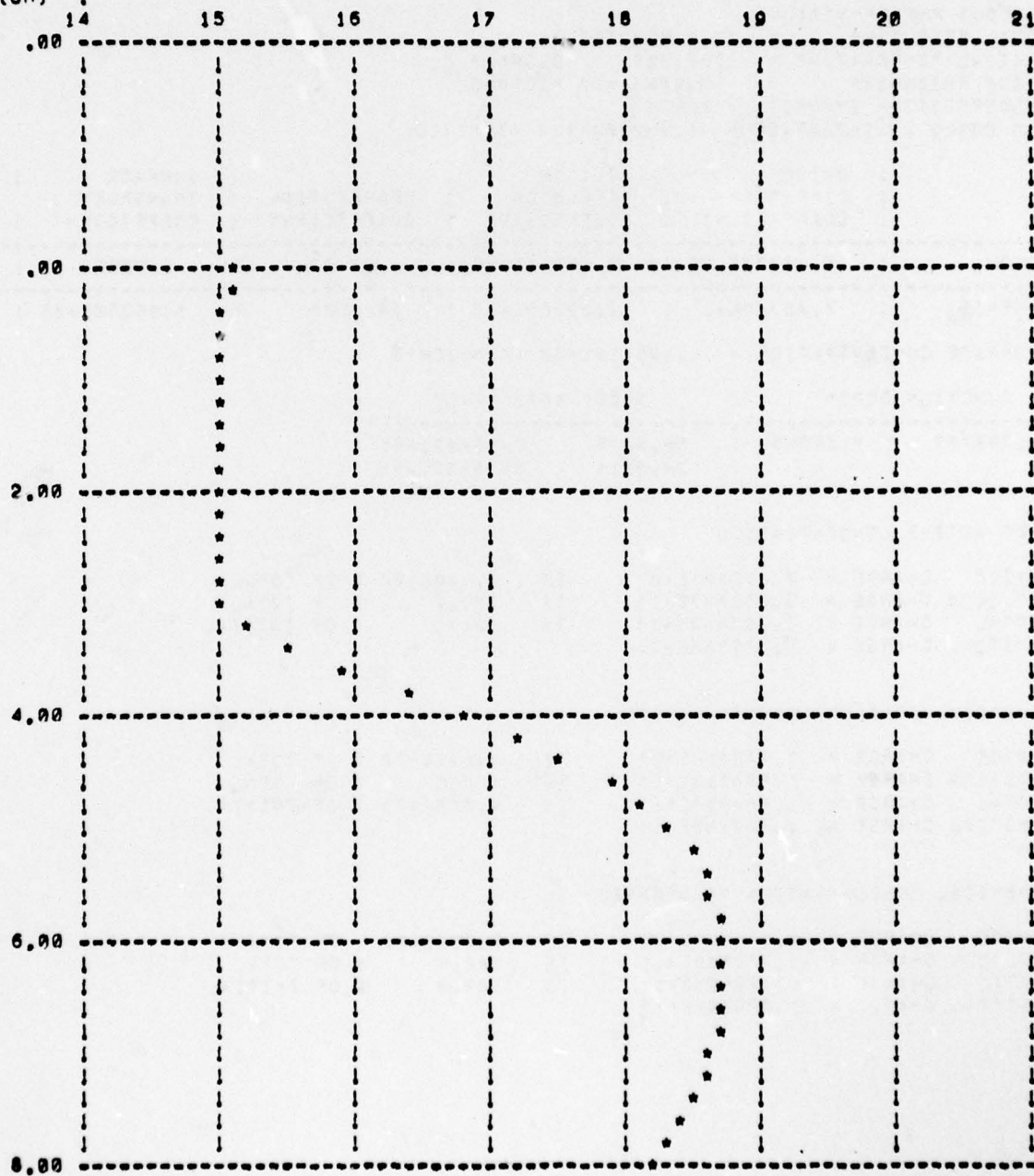
STEP = 7

TIME =

.0 MINUTES.

DEPTH
(UM)

CONCENTRATION (LOG ATOMS/CC)



STANFORD KITCHIP PROCESS
BASE DIFFUSION
STEP # 8

6/5/78

GASEOUS PREDEPOSITION

TOTAL STEP TIME = 30.0 MINUTES
INITIAL TEMPERATURE = 950.000 DEGREES C.
OXIDE THICKNESS = 0.0000E+00 MICRONS
PREDEPOSITION IMPURITY = BORON
GAS CONC. AT INTERFACE = 1.20000E+20 ATOMS/CC

	OXIDE DIFFUSION COEFFICIENT	SILICON DIFFUSION COEFFICIENT	SEGREGATION COEFFICIENT	SURFACE TRANSPORT COEFFICIENT
BORON	5.40472E-09	2.55856E-05	.24457	1.0000
ARSENIC	7.45346E-11	2.22365E-06	10.0000	5.68350E-03

SURFACE CONCENTRATION = 1.196719E+20 ATOMS/CM²

JUNCTION DEPTH	SHEET RESISTANCE
.388777 MICRONS	59.3145 OHMS/SQUARE
	24.8011 OHMS/SQUARE

NET ACTIVE CONCENTRATION

OXIDE CHARGE = 0.220000E+00	IS	0.000E+00	% OF TOTAL
SILICON CHARGE = 3.263642E+15	IS	100.0	% OF TOTAL
TOTAL CHARGE = 3.263642E+15	IS	237.	% OF INITIAL
INITIAL CHARGE = 1.379353E+15			

CHEMICAL CONCENTRATION OF BORON

OXIDE CHARGE = 0.222000E+00	IS	0.000E+00	% OF TOTAL
SILICON CHARGE = 1.884853E+15	IS	100.0	% OF TOTAL
TOTAL CHARGE = 1.884853E+15	IS	4.008E+05	% OF INITIAL
INITIAL CHARGE = 4.722186E+11			

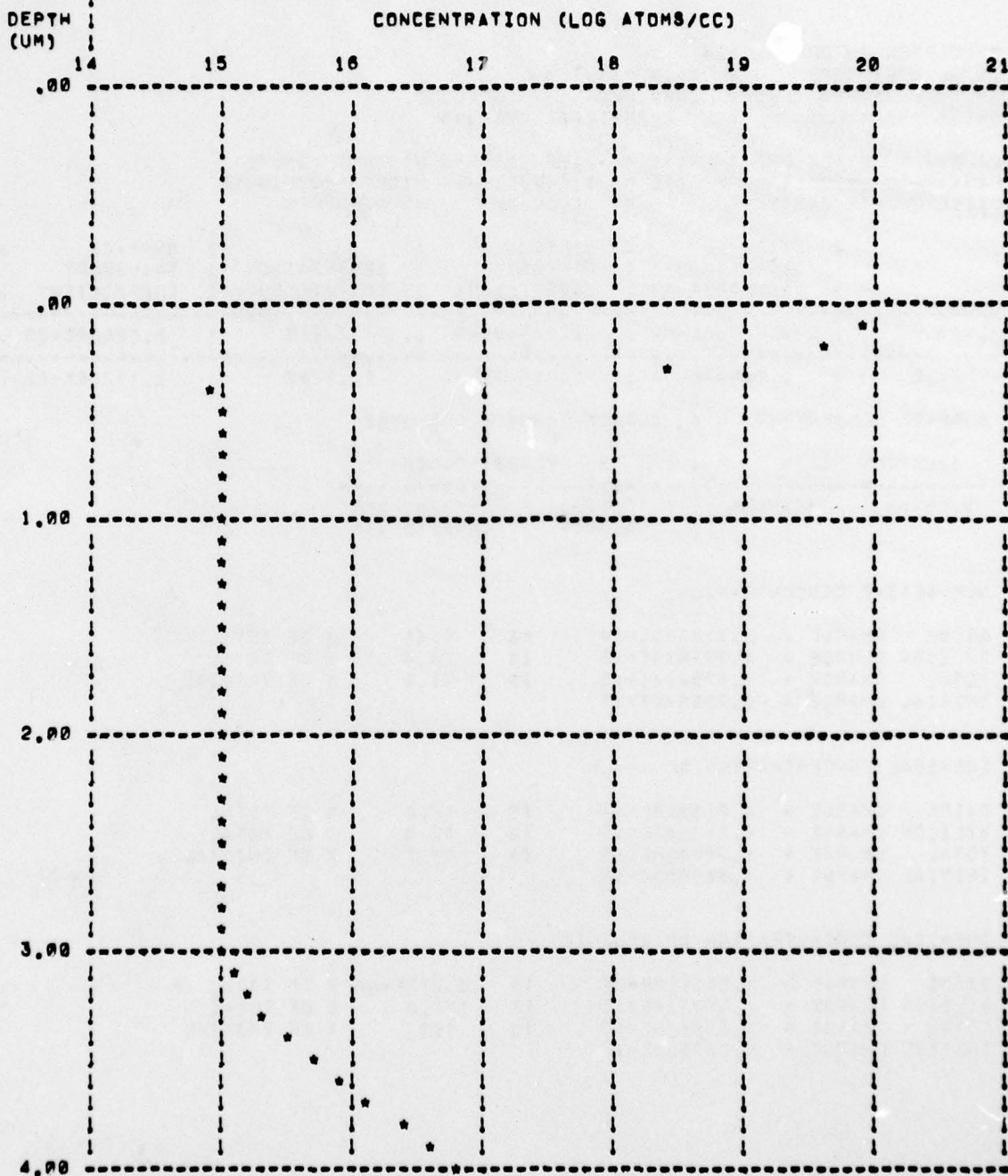
CHEMICAL CONCENTRATION OF ARSENIC

OXIDE CHARGE = 0.220000E+00	IS	0.000E+00	% OF TOTAL
SILICON CHARGE = 1.379826E+15	IS	100.0	% OF TOTAL
TOTAL CHARGE = 1.379826E+15	IS	100.0	% OF INITIAL
INITIAL CHARGE = 1.379827E+15			

STANFORD KITCHIP PROCESS
BASE DIFFUSION

6/5/78

STEP = 8 TIME = 30.0 MINUTES.



STANFORD KITCHIP PROCESS
BASE DIFFUSION
STEP # 9

6/5/78

OXIDATION IN DRY OXYGEN

TOTAL STEP TIME = 45.0 MINUTES
INITIAL TEMPERATURE = 1000.000 DEGREES C.
OXIDE THICKNESS = 4.7021E-02 MICRONS

LINEAR OXIDE GROWTH RATE = 7.994851E-04 MICRONS/MINUTE
PARABOLIC OXIDE GROWTH RATE = 1.807551E-04 MICRONS²/MINUTE
OXIDE GROWTH PRESSURE = 1.00000 ATMOSPHERES

	OXIDE DIFFUSION COEFFICIENT	SILICON DIFFUSION COEFFICIENT	SEGREGATION COEFFICIENT	SURFACE TRANSPORT COEFFICIENT
BORON	2.01368E-08	2.03949E-04	.34974	2.52626E-03
ARSENIC	4.60947E-10	1.01692E-05	10.0000	1.19298E-02

SURFACE CONCENTRATION = 2.542623E+19 ATOMS/CM²

JUNCTION DEPTH	SHEET RESISTANCE
1.03444 MICRONS	73.6273 OHMS/SQUARE
	24.8069 OHMS/SQUARE

NET ACTIVE CONCENTRATION

	IS	% OF TOTAL
OXIDE CHARGE = 2.816303E+14	9.47	% OF TOTAL
SILICON CHARGE = 2.693820E+15	90.5	% OF TOTAL
TOTAL CHARGE = 2.975466E+15	91.2	% OF INITIAL
INITIAL CHARGE = 3.263840E+15		

CHEMICAL CONCENTRATION OF BORON

	IS	% OF TOTAL
OXIDE CHARGE = 2.816390E+14	17.6	% OF TOTAL
SILICON CHARGE = 1.315187E+15	82.4	% OF TOTAL
TOTAL CHARGE = 1.596826E+15	84.7	% OF INITIAL
INITIAL CHARGE = 1.884853E+15		

CHEMICAL CONCENTRATION OF ARSENIC

	IS	% OF TOTAL
OXIDE CHARGE = 7.281110E+08	5.277E-05	% OF TOTAL
SILICON CHARGE = 1.379820E+15	100.0	% OF TOTAL
TOTAL CHARGE = 1.379829E+15	100.	% OF INITIAL
INITIAL CHARGE = 1.379826E+15		

STANFORD KITCHIP PROCESS
BASE DIFFUSION
STEP # 10

6/5/78

OXIDATION IN WET OXYGEN

TOTAL STEP TIME = 60.0 MINUTES
INITIAL TEMPERATURE = 1000.000 DEGREES C.
OXIDE THICKNESS = .4235 MICRONS

LINEAR OXIDE GROWTH RATE = 1.472099E-02 MICRONS/MINUTE
PARABOLIC OXIDE GROWTH RATE = 5.149757E-03 MICRONS²/MINUTE
OXIDE GROWTH PRESSURE = .842105 ATMOSPHERES

	OXIDE DIFFUSION COEFFICIENT	SILICON DIFFUSION COEFFICIENT	SEGREGATION COEFFICIENT	SURFACE TRANSPORT COEFFICIENT
BORON	2.01368E-08	2.03949E-04	.34974	2.52626E-03
ARSENIC	4.60947E-10	1.01692E-05	10.0000	1.19290E-02

SURFACE CONCENTRATION = 3.871102E+18 ATOMS/CM³

JUNCTION DEPTH	SHEET RESISTANCE
1.20266 MICRONS	127.610 OHMS/SQUARE
	24.8019 OHMS/SQUARE

NET ACTIVE CONCENTRATION

OXIDE CHARGE = 9.046204E+14	IS	30.8	% OF TOTAL
SILICON CHARGE = 2.028050E+15	IS	69.2	% OF TOTAL
TOTAL CHARGE = 2.932671E+15	IS	98.6	% OF INITIAL
INITIAL CHARGE = 2.975466E+15			

CHEMICAL CONCENTRATION OF BORON

OXIDE CHARGE = 9.046388E+14	IS	58.2	% OF TOTAL
SILICON CHARGE = 6.494051E+14	IS	41.8	% OF TOTAL
TOTAL CHARGE = 1.554104E+15	IS	97.3	% OF INITIAL
INITIAL CHARGE = 1.596826E+15			

CHEMICAL CONCENTRATION OF ARSENIC

OXIDE CHARGE = 1.845829E+10	IS	1.338E-03	% OF TOTAL
SILICON CHARGE = 1.379807E+15	IS	100.0	% OF TOTAL
TOTAL CHARGE = 1.379825E+15	IS	100.0	% OF INITIAL
INITIAL CHARGE = 1.379829E+15			

STANFORD KITCHIP PROCESS
BASE DIFFUSION
STEP # 11

6/5/78

OXIDATION IN DRY OXYGEN

TOTAL STEP TIME = 5.0 MINUTES
INITIAL TEMPERATURE = 1000.000 DEGREES C.
OXIDE THICKNESS = .4243 MICRONS

LINEAR OXIDE GROWTH RATE = 7.885412E-04 MICRONS/MINUTE
PARABOLIC OXIDE GROWTH RATE = 1.795514E-04 MICRONS²/MINUTE
OXIDE GROWTH PRESSURE = 1.00000 ATMOSPHERES

	OXIDE DIFFUSION COEFFICIENT	SILICON DIFFUSION COEFFICIENT	SEGREGATION COEFFICIENT	SURFACE TRANSPORT COEFFICIENT
BORON	2.01368E-08	2.03949E-04	.34974	2.52626E-03
ARSENIC	4.60947E-10	1.01692E-05	10.0000	1.19298E-02

SURFACE CONCENTRATION = 5.871862E+18 ATOMS/CM²

JUNCTION DEPTH	SHEET RESISTANCE
1.22169 MICRONS	128.319 OHMS/SQUARE
	24.7965 OHMS/SQUARE

NET ACTIVE CONCENTRATION

CHARGE	IS	% OF TOTAL
OXIDE CHARGE = 9.127785E+14	31.1	% OF TOTAL
SILICON CHARGE = 2.019751E+15	68.9	% OF TOTAL
TOTAL CHARGE = 2.932529E+15	100.0	% OF INITIAL
INITIAL CHARGE = 2.932671E+15		

CHEMICAL CONCENTRATION OF BORON

CHARGE	IS	% OF TOTAL
OXIDE CHARGE = 9.127969E+14	58.7	% OF TOTAL
SILICON CHARGE = 6.411452E+14	41.3	% OF TOTAL
TOTAL CHARGE = 1.553942E+15	100.0	% OF INITIAL
INITIAL CHARGE = 1.554104E+15		

CHEMICAL CONCENTRATION OF ARSENIC

CHARGE	IS	% OF TOTAL
OXIDE CHARGE = 1.837133E+10	1.331E-03	% OF TOTAL
SILICON CHARGE = 1.379832E+15	100.0	% OF TOTAL
TOTAL CHARGE = 1.379850E+15	100.	% OF INITIAL
INITIAL CHARGE = 1.379825E+15		

STANFORD KITCHIP PROCESS
BASE DIFFUSION
STEP # 12

6/5/78

NEUTRAL AMBIENT DRIVE-IN

TOTAL STEP TIME = 10.0 MINUTES
INITIAL TEMPERATURE = 1000.000 DEGREES C.
OXIDE THICKNESS = .4243 MICRONS

	OXIDE DIFFUSION COEFFICIENT	SILICON DIFFUSION COEFFICIENT	SEGREGATION COEFFICIENT	SURFACE TRANSPORT COEFFICIENT
BORON	2.01368E-08	9.16197E-05	.34974	2.52626E-03
ARSENIC	4.60947E-10	1.01692E-05	10.0000	1.19298E-02

SURFACE CONCENTRATION = 6.891920E+18 ATOMS/CM²

JUNCTION DEPTH	SHEET RESISTANCE
1.24112 MICRONS	128.388 OHMS/SQUARE
	24.7988 OHMS/SQUARE

NET ACTIVE CONCENTRATION

OXIDE CHARGE	= 9.162638E+14	IS	31.2	% OF TOTAL
SILICON CHARGE	= 2.016200E+15	IS	68.8	% OF TOTAL
TOTAL CHARGE	= 2.932464E+15	IS	100.0	% OF INITIAL
INITIAL CHARGE	= 2.932529E+15			

CHEMICAL CONCENTRATION OF BORON

OXIDE CHARGE	= 9.162021E+14	IS	59.0	% OF TOTAL
SILICON CHARGE	= 6.375986E+14	IS	41.0	% OF TOTAL
TOTAL CHARGE	= 1.553881E+15	IS	100.0	% OF INITIAL
INITIAL CHARGE	= 1.553942E+15			

CHEMICAL CONCENTRATION OF ARSENIC

OXIDE CHARGE	= 1.829183E+10	IS	1.326E-03	% OF TOTAL
SILICON CHARGE	= 1.379832E+15	IS	100.0	% OF TOTAL
TOTAL CHARGE	= 1.379850E+15	IS	100.0	% OF INITIAL
INITIAL CHARGE	= 1.379850E+15			

STANFORD KITCHIP PROCESS
BASE DIFFUSION
STEP # 13

6/5/78

ETCH STEP

ETCH TEMPERATURE = 25.0 DEGREES C.
ETCH TIME = .0 MINUTES
ETCH RATE = .0000 MICRONS/MINUTE
OXIDE THICKNESS = 0.0000E+00 MICRONS

SURFACE CONCENTRATION = 6.891920E+18 ATOMS/CM³

JUNCTION DEPTH	SHEET RESISTANCE
1.23930 MICRONS	128.389 OHMS/SQUARE
	24.7956 OHMS/SQUARE

NET ACTIVE CONCENTRATION

OXIDE CHARGE = 0.000000E+00	IS 0.000E+00 % OF TOTAL
SILICON CHARGE = 2.016181E+15	IS 100.0 % OF TOTAL
TOTAL CHARGE = 2.016181E+15	IS 68.8 % OF INITIAL
INITIAL CHARGE = 2.932464E+15	

CHEMICAL CONCENTRATION OF BORON

OXIDE CHARGE = 0.000000E+00	IS 0.000E+00 % OF TOTAL
SILICON CHARGE = 6.375974E+14	IS 100.0 % OF TOTAL
TOTAL CHARGE = 6.375974E+14	IS 41.0 % OF INITIAL
INITIAL CHARGE = 1.553881E+15	

CHEMICAL CONCENTRATION OF ARSENIC

OXIDE CHARGE = 0.000000E+00	IS 0.000E+00 % OF TOTAL
SILICON CHARGE = 1.379814E+15	IS 100.0 % OF TOTAL
TOTAL CHARGE = 1.379814E+15	IS 100.0 % OF INITIAL
INITIAL CHARGE = 1.379850E+15	

STANFORD KITCHIP PROCESS

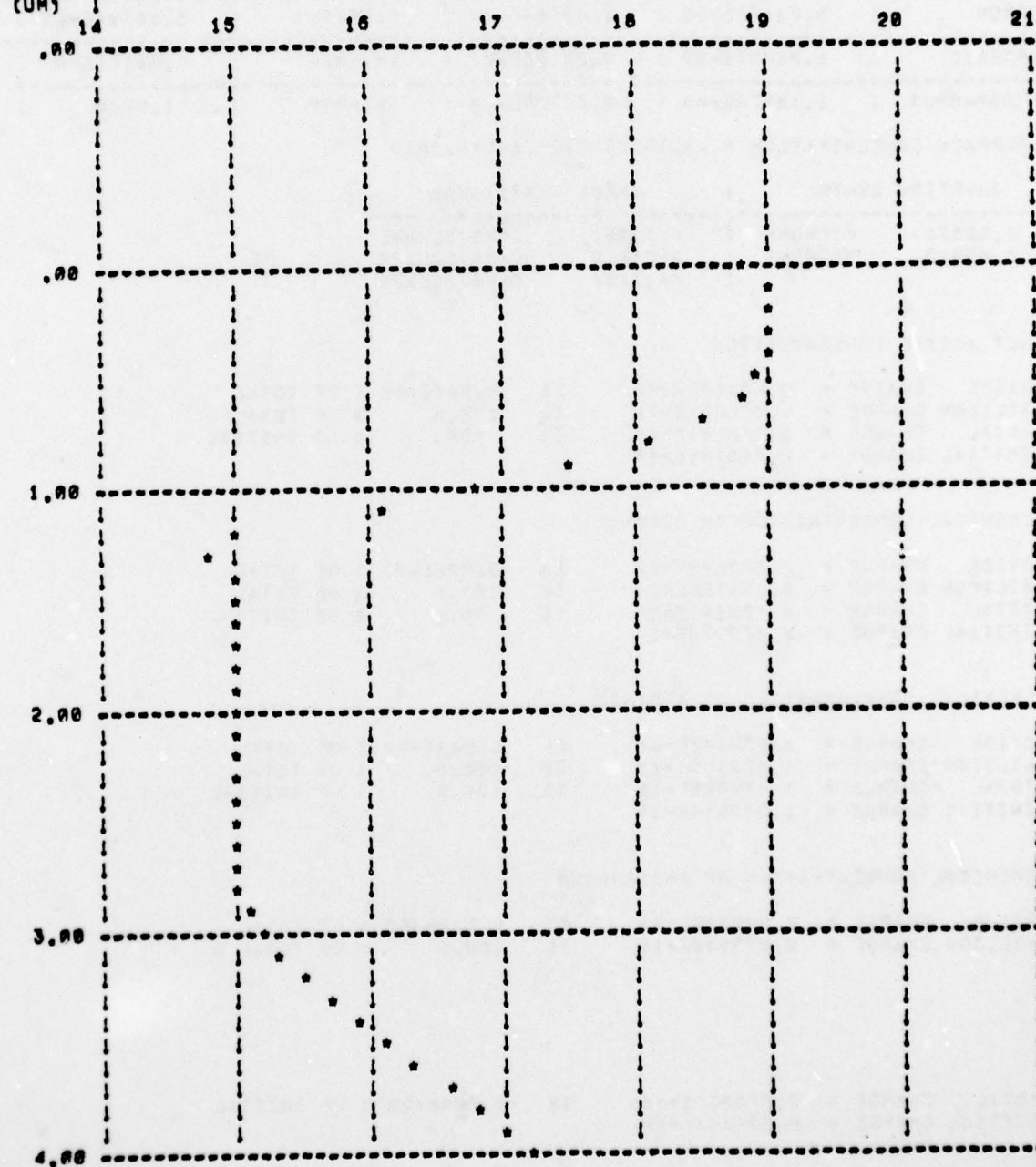
6/5/78

BASE DIFFUSION

STEP = 13 TIME = .8 MINUTES.

DEPTH
(UM)

CONCENTRATION (LOG ATOMS/CC)



STANFORD KITCHIP PROCESS
 EMITTER DIFFUSION
 STEP # 14

6/5/78

GASEOUS PREDEPOSITION

TOTAL STEP TIME = 33.8 MINUTES
 INITIAL TEMPERATURE = 1025.00 DEGREES C.
 OXIDE THICKNESS = 0.0000E+00 MICRONS
 PREDEPOSITION IMPURITY = PHOSPHORUS
 GAS CONC. AT INTERFACE = 1.150000E+21 ATOMS/CC

	OXIDE DIFFUSION COEFFICIENT	SILICON DIFFUSION COEFFICIENT	SEGREGATION COEFFICIENT	SURFACE TRANSPORT COEFFICIENT
BORON	3.74197E-08	1.67164E-04	.41393	3.90494E-03
ARSENIC	1.08752E-09	2.08126E-05	10.0000	1.69177E-02
PHOSPHORUS	1.17679E-06	2.56709E-04	10.0000	1.0000

SURFACE CONCENTRATION = 3.390586E+20 ATOMS/CM²

JUNCTION DEPTH		SHEET RESISTANCE
1.08376	MICRONS	6.73281 OHMS/SQUARE
1.55913	MICRONS	26066.9 OHMS/SQUARE
		24.7757 OHMS/SQUARE

NET ACTIVE CONCENTRATION

OXIDE CHARGE = 0.000000E+00 IS 0.000E+00 % OF TOTAL
 SILICON CHARGE = 1.370081E+16 IS 100.0 % OF TOTAL
 TOTAL CHARGE = 1.370081E+16 IS 680. % OF INITIAL
 INITIAL CHARGE = 2.016181E+15

CHEMICAL CONCENTRATION OF BORON

OXIDE CHARGE = 0.000000E+00 IS 0.000E+00 % OF TOTAL
 SILICON CHARGE = 6.125195E+14 IS 100.0 % OF TOTAL
 TOTAL CHARGE = 6.125195E+14 IS 96.1 % OF INITIAL
 INITIAL CHARGE = 6.375974E+14

CHEMICAL CONCENTRATION OF ARSENIC

OXIDE CHARGE = 0.000000E+00 IS 0.000E+00 % OF TOTAL
 SILICON CHARGE = 1.379805E+15 IS 100.0 % OF TOTAL
 TOTAL CHARGE = 1.379805E+15 IS 100.0 % OF INITIAL
 INITIAL CHARGE = 1.379814E+15

CHEMICAL CONCENTRATION OF PHOSPHORUS

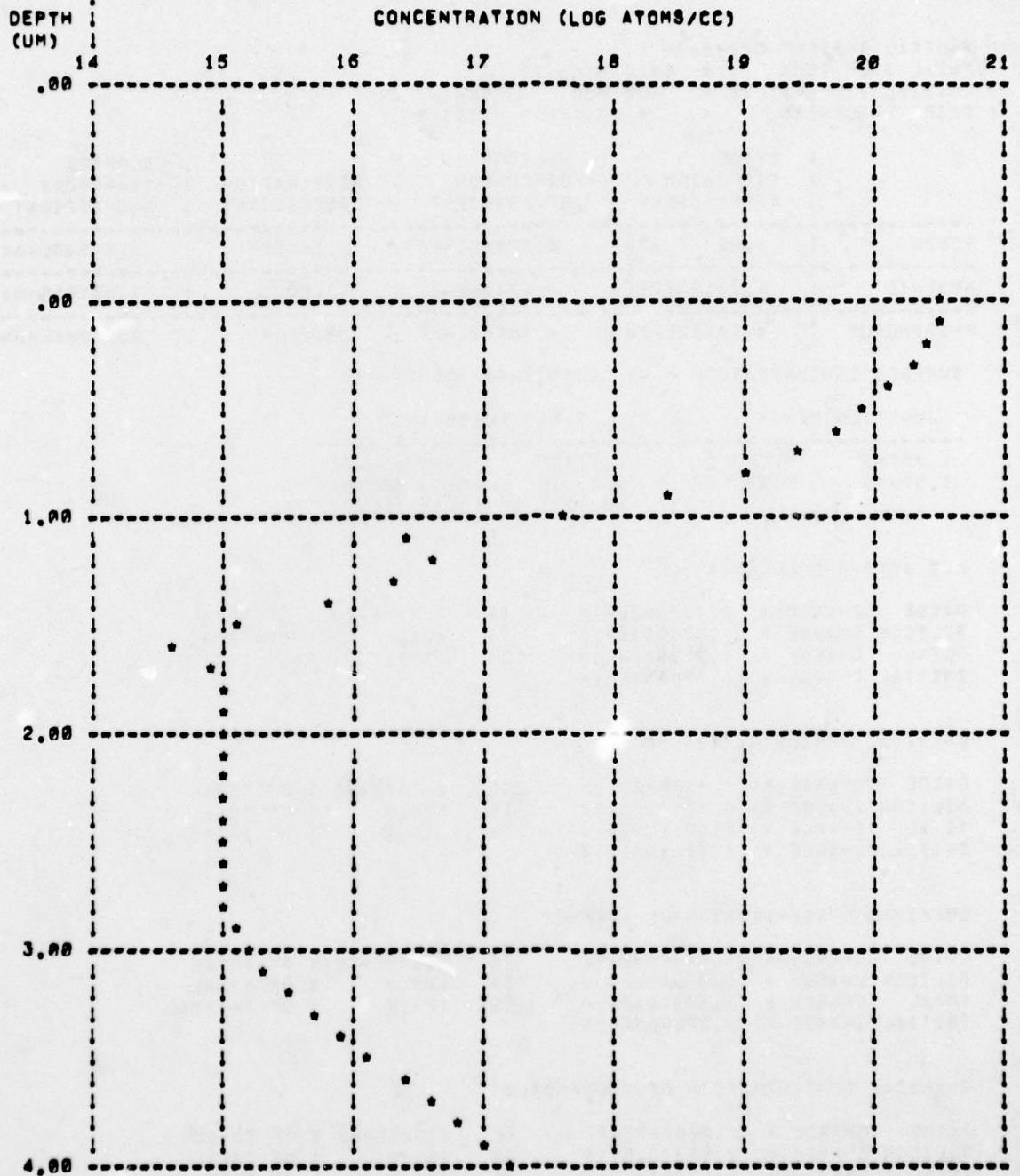
OXIDE CHARGE = 0.000000E+00 IS 0.000E+00 % OF TOTAL
 SILICON CHARGE = 2.973232E+16 IS 100.0 % OF TOTAL

TOTAL CHARGE = 2.973232E+16 IS 0.000E+00 % OF INITIAL
 INITIAL CHARGE = 0.000000E+00

STANFORD KITCHIP PROCESS
 EMITTER DIFFUSION

6/5/78

STEP = 14 TIME = 33.0 MINUTES.



STANFORD KITCHIP PROCESS
 EMITTER DIFFUSION
 STEP # 15

6/5/78

NEUTRAL AMBIENT DRIVE-IN

TOTAL STEP TIME = 10.0 MINUTES
 INITIAL TEMPERATURE = 900.000 DEGREES C.
 OXIDE THICKNESS = 0.0000E+00 MICRONS

	OXIDE DIFFUSION COEFFICIENT	SILICON DIFFUSION COEFFICIENT	SEGREGATION COEFFICIENT	SURFACE TRANSPORT COEFFICIENT
BORON	1.29677E-09	6.39843E-06	.16589	3.67548E-04
ARSENIC	1.03185E-11	4.27144E-07	10.0000	2.54185E-03
PHOSPHORUS	4.19632E-08	4.36669E-06	10.0000	0.00000E+00

SURFACE CONCENTRATION = -3.322567E+20 ATOMS/CM³

JUNCTION DEPTH		SHEET RESISTANCE
1.08766 MICRONS		6.71579 OHMS/SQUARE
1.56485 MICRONS		26019.8 OHMS/SQUARE
		24.7739 OHMS/SQUARE

NET ACTIVE CONCENTRATION

OXIDE CHARGE = 0.000000E+00 IS 0.000E+00 % OF TOTAL
 SILICON CHARGE = 1.372984E+16 IS 100.0 % OF TOTAL
 TOTAL CHARGE = 1.372984E+16 IS 100. % OF INITIAL
 INITIAL CHARGE = 1.370081E+16

CHEMICAL CONCENTRATION OF BORON

OXIDE CHARGE = 0.000000E+00 IS 0.000E+00 % OF TOTAL
 SILICON CHARGE = 6.121120E+14 IS 100.0 % OF TOTAL
 TOTAL CHARGE = 6.121120E+14 IS 99.9 % OF INITIAL
 INITIAL CHARGE = 6.125195E+14

CHEMICAL CONCENTRATION OF ARSENIC

OXIDE CHARGE = 0.000000E+00 IS 0.000E+00 % OF TOTAL
 SILICON CHARGE = 1.379804E+15 IS 100.0 % OF TOTAL
 TOTAL CHARGE = 1.379804E+15 IS 100.0 % OF INITIAL
 INITIAL CHARGE = 1.379805E+15

CHEMICAL CONCENTRATION OF PHOSPHORUS

OXIDE CHARGE = 0.000000E+00 IS 0.000E+00 % OF TOTAL
 SILICON CHARGE = 2.973231E+16 IS 100.0 % OF TOTAL
 TOTAL CHARGE = 2.973231E+16 IS 100.0 % OF INITIAL
 INITIAL CHARGE = 2.973232E+16

STANFORD KITCHIP PROCESS
EMITTER DIFFUSION
STEP # 16

6/5/78

OXIDATION IN WET OXYGEN

TOTAL STEP TIME = 10.0 MINUTES
INITIAL TEMPERATURE = 900.000 DEGREES C.
OXIDE THICKNESS = .1777 MICRONS

LINEAR OXIDE GROWTH RATE = 5.628432E-02 MICRONS/MINUTE
PARABOLIC OXIDE GROWTH RATE = 4.581483E-03 MICRONS²/MINUTE
OXIDE GROWTH PRESSURE = .842105 ATMOSPHERES

	OXIDE DIFFUSION COEFFICIENT	SILICON DIFFUSION COEFFICIENT	SEGREGATION COEFFICIENT	SURFACE TRANSPORT COEFFICIENT
BORON	1.29677E-09	3.66143E-05	.16589	3.67548E-04
ARSENIC	1.03185E-11	4.27144E-07	10.0000	2.54185E-03
PHOSPHORUS	4.19632E-08	7.86005E-06	10.0000	0.00000E+00

SURFACE CONCENTRATION = -5.197845E+20 ATOMS/CM²

JUNCTION DEPTH	SHEET RESISTANCE
1.00799 MICRONS	8.25491 OHMS/SQUARE
1.49109 MICRONS	24321.2 OHMS/SQUARE
	24.7715 OHMS/SQUARE

NET ACTIVE CONCENTRATION

OXIDE CHARGE = 3.463763E+15 IS 23.4 % OF TOTAL
SILICON CHARGE = 1.135358E+16 IS 76.6 % OF TOTAL
TOTAL CHARGE = 1.481735E+16 IS 100. % OF INITIAL
INITIAL CHARGE = 1.372984E+16

CHEMICAL CONCENTRATION OF BORON

OXIDE CHARGE = 4.604792E+13 IS 7.55 % OF TOTAL
SILICON CHARGE = 5.639213E+14 IS 92.5 % OF TOTAL
TOTAL CHARGE = 6.099692E+14 IS 99.6 % OF INITIAL
INITIAL CHARGE = 6.121120E+14

CHEMICAL CONCENTRATION OF ARSENIC

OXIDE CHARGE = 3.248591E+09 IS 2.354E-04 % OF TOTAL
SILICON CHARGE = 1.379806E+15 IS 100.0 % OF TOTAL
TOTAL CHARGE = 1.379809E+15 IS 100. % OF INITIAL
INITIAL CHARGE = 1.379804E+15

CHEMICAL CONCENTRATION OF PHOSPHORUS

OXIDE CHARGE = 6.676253E+15 IS 22.3 % OF TOTAL
SILICON CHARGE = 2.322669E+16 IS 77.7 % OF TOTAL
TOTAL CHARGE = 2.990294E+16 IS 101. % OF INITIAL
INITIAL CHARGE = 2.973231E+16

STANFORD KITCHIP PROCESS
EMITTER DIFFUSION
STEP # 17

6/5/78

NEUTRAL AMBIENT DRIVE-IN

TOTAL STEP TIME = 10.0 MINUTES
INITIAL TEMPERATURE = 900.000 DEGREES C.
OXIDE THICKNESS = .1777 MICRONS

	OXIDE DIFFUSION COEFFICIENT	SILICON DIFFUSION COEFFICIENT	SEGREGATION COEFFICIENT	SURFACE TRANSPORT COEFFICIENT
BORON	1.29677E-09	6.39843E-06	.16589	3.67548E-04
ARSENIC	1.03185E-11	4.27144E-07	10.0000	2.54185E-03
PHOSPHORUS	4.19632E-08	4.36669E-06	10.0000	0.00000E+00

SURFACE CONCENTRATION = -4.416995E+20 ATOMS/CM³

JUNCTION DEPTH		SHEET RESISTANCE
1.00908 MICRONS		8.20940 OHMS/SQUARE
1.49193 MICRONS		24343.0 OHMS/SQUARE
		24.7713 OHMS/SQUARE

NET ACTIVE CONCENTRATION

OXIDE CHARGE =	3.403248E+15	IS	23.0	% OF TOTAL
SILICON CHARGE =	1.141275E+16	IS	77.0	% OF TOTAL
TOTAL CHARGE =	1.481600E+16	IS	100.0	% OF INITIAL
INITIAL CHARGE =	1.481735E+16			

CHEMICAL CONCENTRATION OF BORON

OXIDE CHARGE =	4.670280E+13	IS	7.66	% OF TOTAL
SILICON CHARGE =	5.629458E+14	IS	92.3	% OF TOTAL
TOTAL CHARGE =	6.096486E+14	IS	99.9	% OF INITIAL
INITIAL CHARGE =	6.099692E+14			

CHEMICAL CONCENTRATION OF ARSENIC

OXIDE CHARGE =	3.166797E+09	IS	2.295E-04	% OF TOTAL
SILICON CHARGE =	1.379806E+15	IS	100.0	% OF TOTAL
TOTAL CHARGE =	1.379809E+15	IS	100.0	% OF INITIAL
INITIAL CHARGE =	1.379809E+15			

CHEMICAL CONCENTRATION OF PHOSPHORUS

OXIDE CHARGE =	6.490390E+15	IS	21.7	% OF TOTAL
SILICON CHARGE =	2.341254E+16	IS	78.3	% OF TOTAL
TOTAL CHARGE =	2.990293E+16	IS	100.0	% OF INITIAL
INITIAL CHARGE =	2.990294E+16			

6/5/78

ENTERIC DIFFUSION

STANFORD KITCHIP PROCESS 6/5/
EMITTER DIFFUSION
1 STEP = 17 TIME = 10.0 MINUTES.

